Neutrons: from nuclear forces to nanotechnology

N.A. Fedorov,
FLNP JINR
nfedorov@jinr.ru

CONTENTS OF TALK

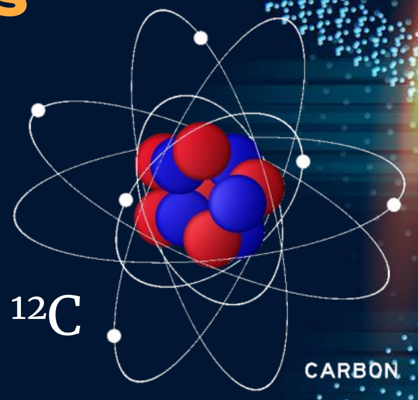
1. Bascic concepts and a little historical rewiev.
2. Structure of the FLNP.
3. Neutron sources.
4. Research fields:
   - Nuclear physics.
   - Condensed matter physics.

Basic nuclear physics concepts

- Atomic nucleus are designated like ^{A}Z where A – mass number and Z – symbol of element.
- Nuclear reaction – process which changes intrinsic structure of nuclei. It is ordinary written as A(a,b)B or a+A→b+B
- Q-value of reaction:

$$Q = m_a + m_A - m_b - m_B$$

- If Q > 0, energy is released.
- If Q < 0, energy is absorbed (additional energy is needed to ignite the reaction)



Discovery of neutron (1932)

Atomic nucleus was discovered by E. Rutherford in 1913.
Nucleus consists of:

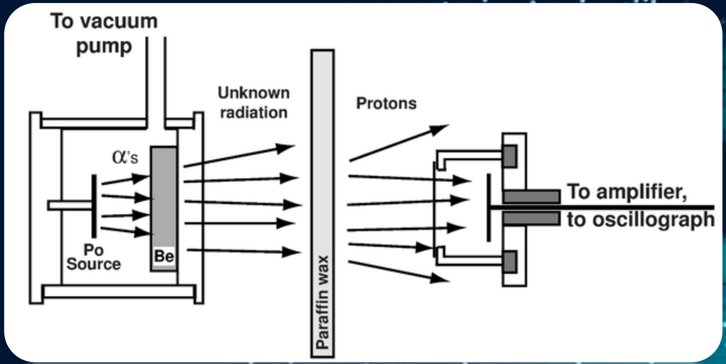
- Protons
- Unknown particles (Bound states of *p* and *e*?)

What is born during Beryllium irradiation by α-particles?
(γ-quanta? New particle?)

$$E_\gamma = \frac{-E_p \pm \sqrt{{E_p}^2 + m_p c^2 E_p}}{4}$$, E_p~5 MeV → E_γ=33 MeV (it is too much!)

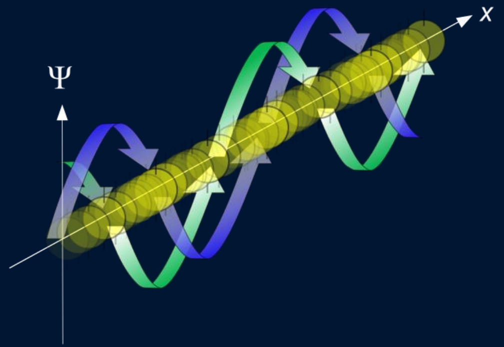
(Q-value of $^{9}Be(\alpha,\gamma)^{13}C$ is 11 MeV)
(Q-value of $^{9}Be(\alpha,n)^{12}C$ is 5.7 MeV)


J. Chadwick

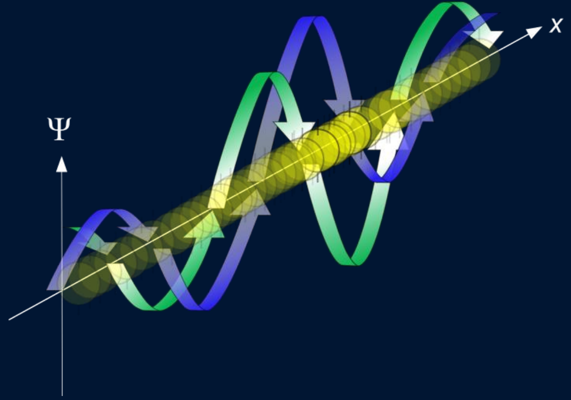


Waves of matter

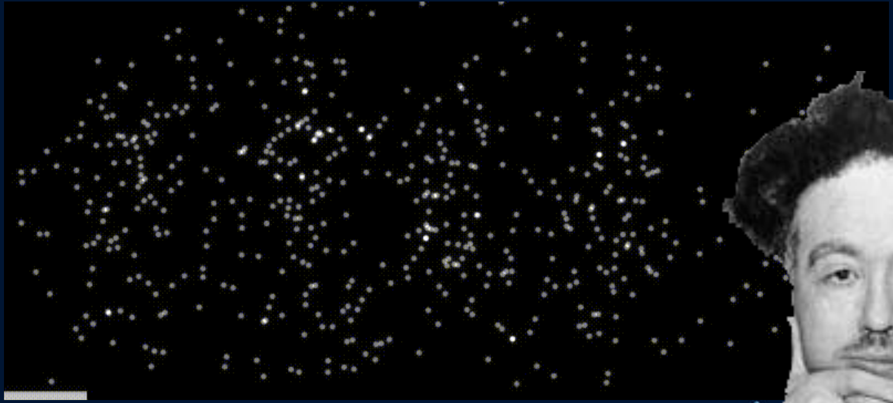
$$\Psi = Ae^{i(kx - \omega t)}$$



$$\Psi = \sum_n A_n e^{i(k_n x - \omega_n t)}$$



Subatomic particles demonstrate wave behavior
(Davisson–Germer experiment with electron diffraction, 1923)



$$\lambda = \frac{h}{p} = 2\pi \frac{\hbar c}{pc}$$

Neutron waves

Group		Energy band E_n, eV	Wavelength λ_n	Structures	Available in FLNP
Slow	Ultracold	$< 3 \cdot 10^{-7}$	>500 Å	Macroscopic	No :(
	Cold	$3 \cdot 10^{-7} - 0{,}025$	1.8 – 500 Å	Molecules and crystals	Yes!
	Thermal	$0{,}025 - 0{,}5$	0,4 – 1,8 Å	Crystals, nuclei	Yes!
	Resonance	$0{,}5 - 10^{3}$	0,01 – 0.4 Å	Nuclei	Yes!
	Intermediate	$10^{3} - 100 \cdot 10^{3}$	100 – 1000 Fm	Nuclei	Yes!
Fast		$> 100 \cdot 10^{3}$	<100 Fm	Nuclei	Yes!

$$\lambda_n = \frac{h}{p_n} = 2\pi \frac{\hbar c}{p_n c} = \frac{2\pi \hbar c}{\sqrt{2 E_n m_n c^2}}$$

1Å $= 10^{-10}$ m

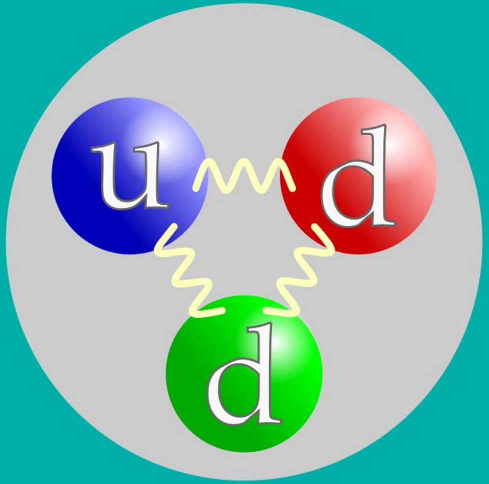
1Fm $= 10^{-15}$ m

Meet our hero!

- Neutral baryon
- Nucleon (part of atomic nuclei)
- Participates in all known interactions
- Has a magnetic moment
    - It is not a fundamental (structureless) particle
    - It is sensitive to a magnetic field

Puzzles of neutron:

- Lifetime problem (difference between trap and beam methods)
- Question about electric dipole moment
- Stringency of baryon number conservation law



$m_n = 939{,}565$ MeV

$\tau_t = 877{,}75 \pm 0.28$ sec

$\tau_b = 888 \pm 2$ sec

$q = 0$

$s = 1/2\hbar$

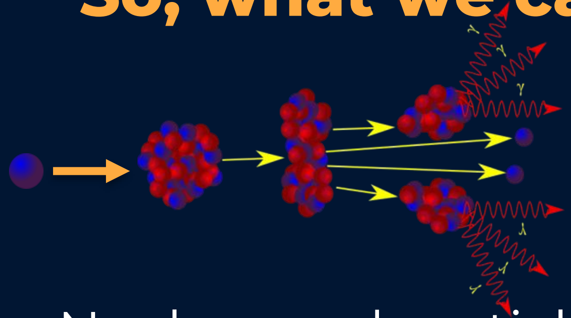
Moderation of neutrons

- Neutrons are produced in nuclear reactions with energies of several MeV. Often it is too much!
- Elastic and inelastic collisions – a way to slow down

$$E_n = \frac{(A+1)^2}{A^2+1} E_{n-1}$$

- Until thermodynamic equilibrium $E_n^{нв} = k_B T; \langle E_n \rangle = \frac{3}{2} k_B T$

So, what we can study with neutrons?

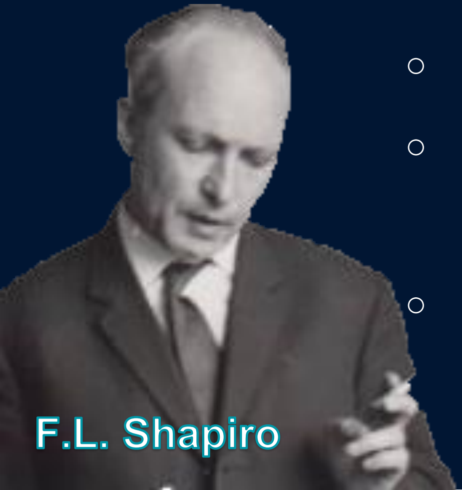


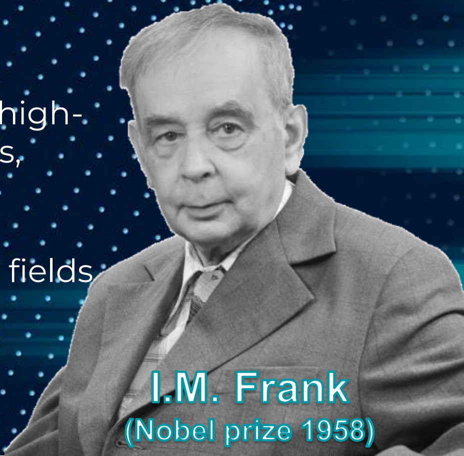
- Nuclear and particle physics
- Solid state physics
- Applied research
(elemental and structural analysis)

Frank Laboratory of Neutron Physics
FLNP

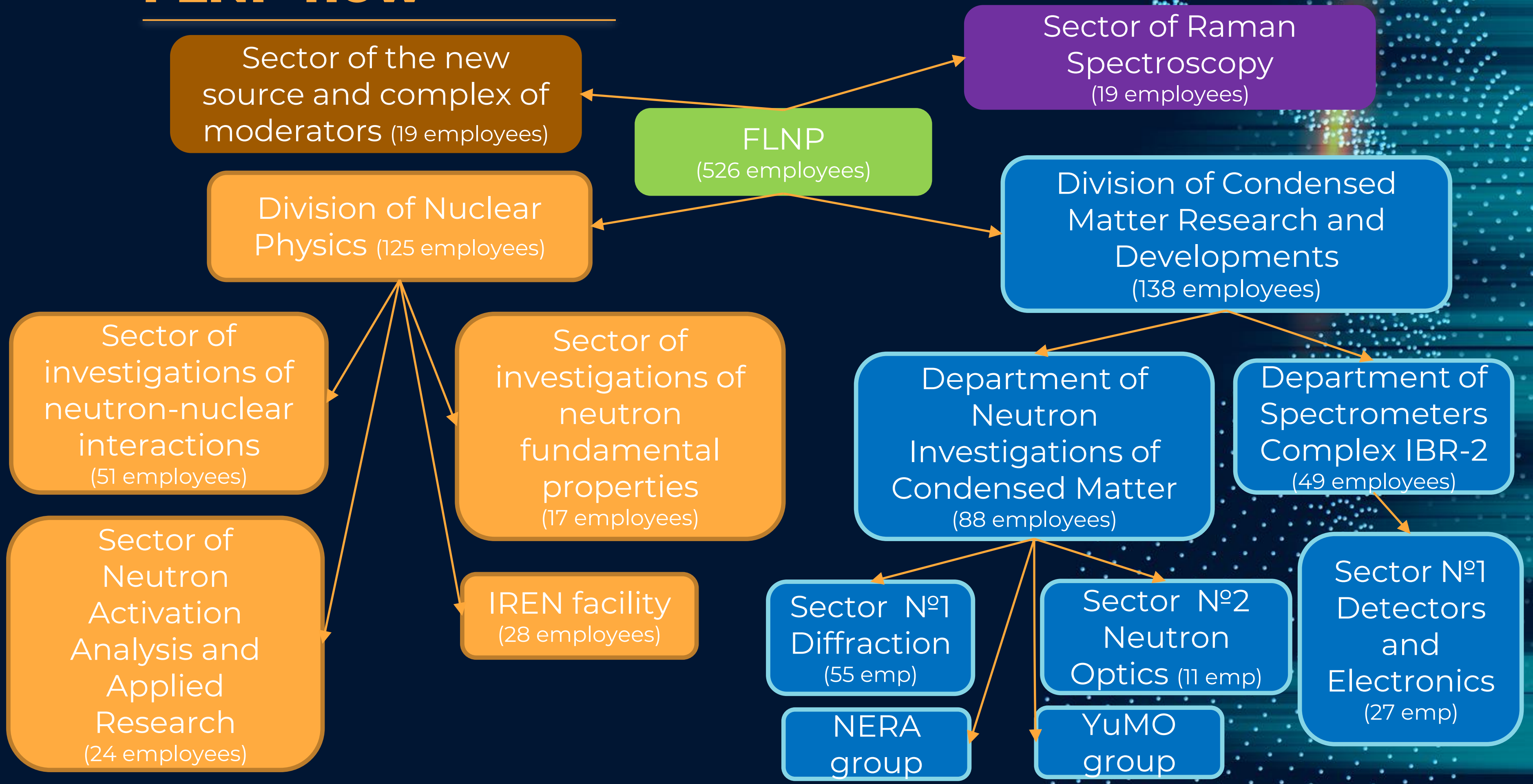
- Established in 1956
- Unique basic facility: IBR pulse reactor (launched 06.23.1960)

- Discovered/made for the fist time:
  - ultracold neutrons
  - neutron polarization by scattering on polarized protons
  - temporal neutron focusing
  - systematics for p-resonance neutron scattering, properties of high-energy excited states (decay probabilities, γ-strength functions, magnetic moments)
  - magnetic structures of substance under in extreme magnetic fields (12Tl)


F.L. Shapiro


I.M. Frank
(Nobel prize 1958)

FLNP now


FLNP (526 employees)
Sector of the new source and complex of moderators (19 employees)
Sector of Raman Spectroscopy (19 employees)
Division of Nuclear Physics (125 employees)
Division of Condensed Matter Research and Developments (138 employees)
Sector of investigations of neutron-nuclear interactions (51 employees)
Sector of investigations of neutron fundamental properties (17 employees)
Sector of Neutron Activation Analysis and Applied Research (24 employees)
IREN facility (28 employees)
Department of Neutron Investigations of Condensed Matter (88 employees)
Department of Spectrometers Complex IBR-2 (49 employees)
Sector №1 Diffraction (55 emp)
Sector №2 Neutron Optics (11 emp)
Sector №1 Detectors and Electronics (27 emp)
NERA group
YuMO group

FLNP neutron sources

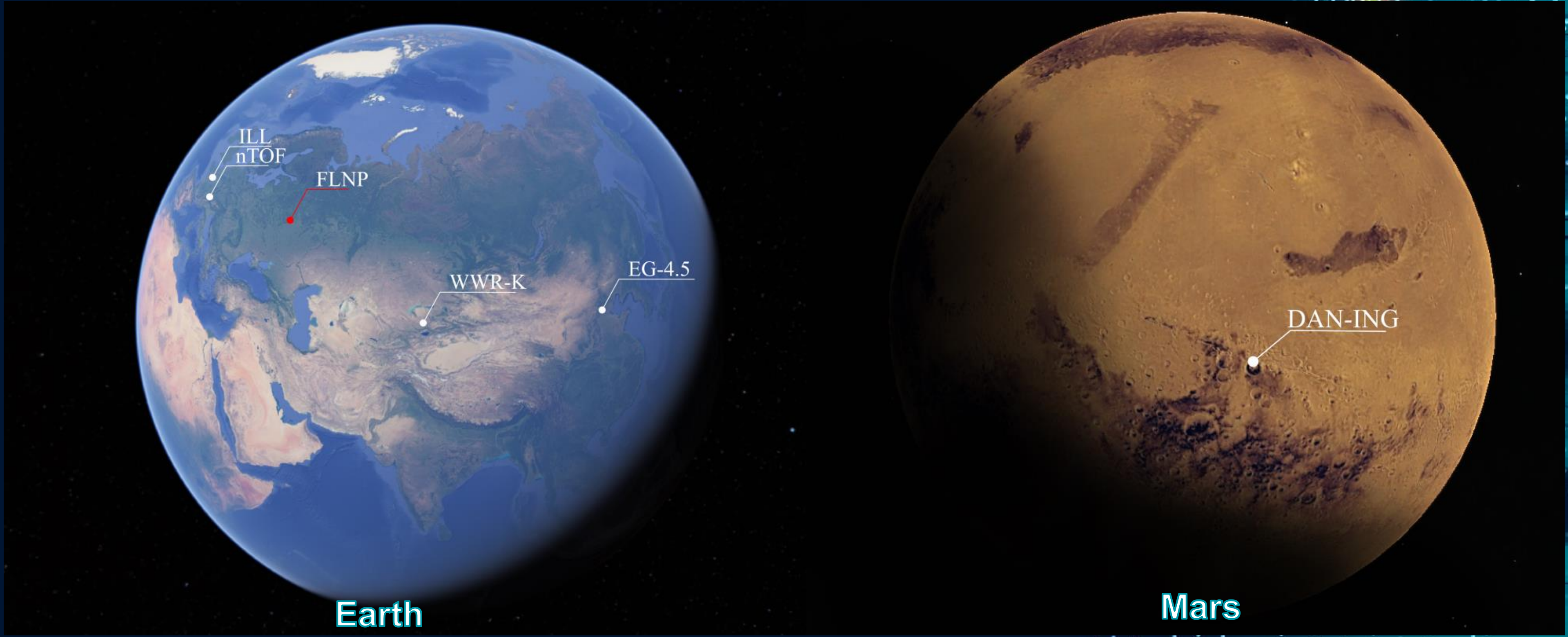
- IBR-2 pulse reactor (repairing)
- IREN facility
- EG-5 – based neutron generator (reconstruction)
- DD and DT industrial neutron generators
- PuBe, AmBe and ^{252}Cf radioactive neutron sources
- **NEPTUN (replacement of IBR in 2040-s)**

(see A. Hassan report)

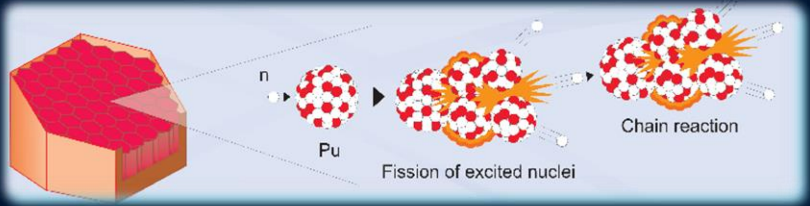
Collaborator’s neutron sources

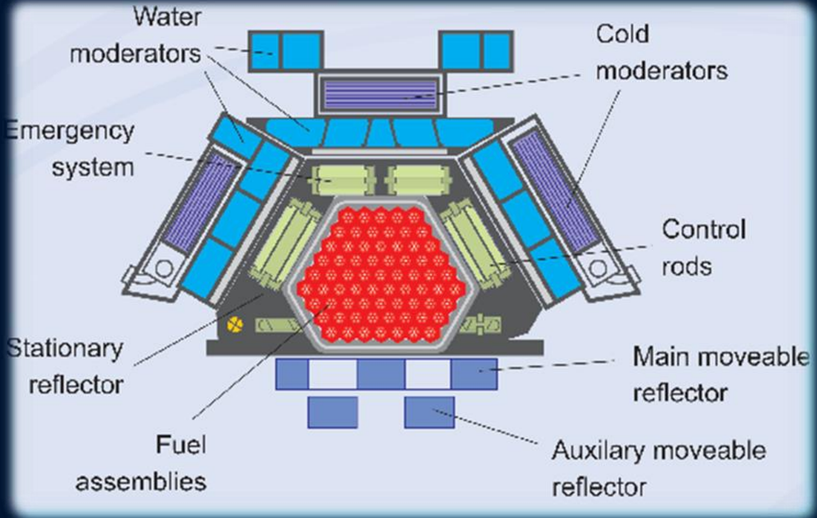
- nTOF (CERN)
- ILL reactor (Grenoble, France)
- EG-4,5 (Beijing, China)
- WWR-K (Almaty, Kazakhstan)

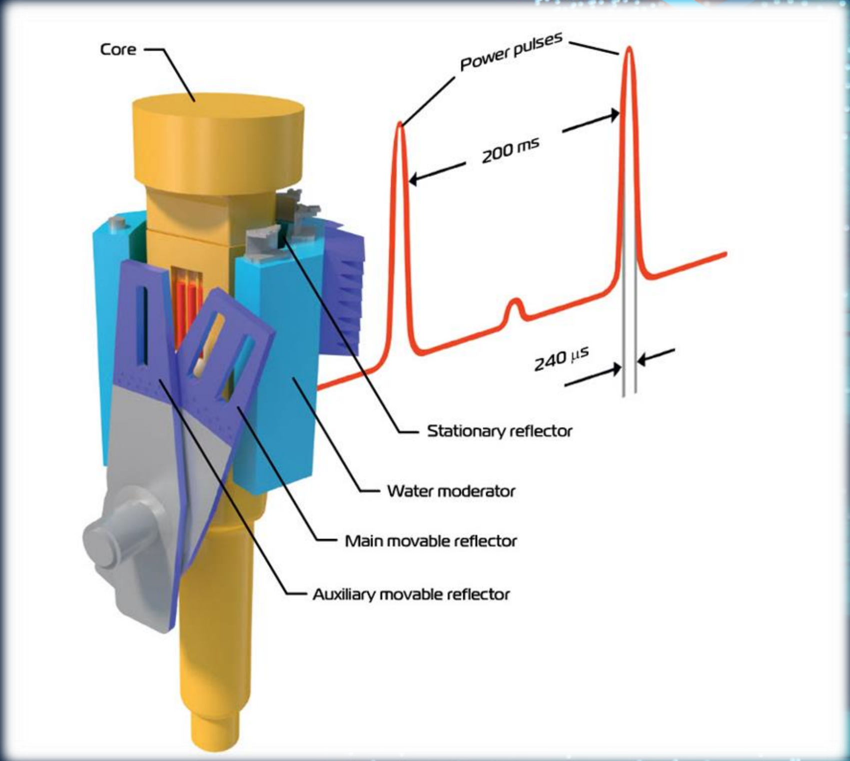
Locations of avalible neutron sources



IBR-2 pulsed reactor





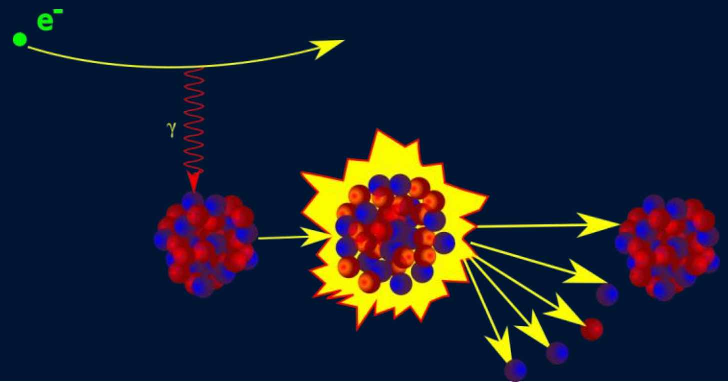


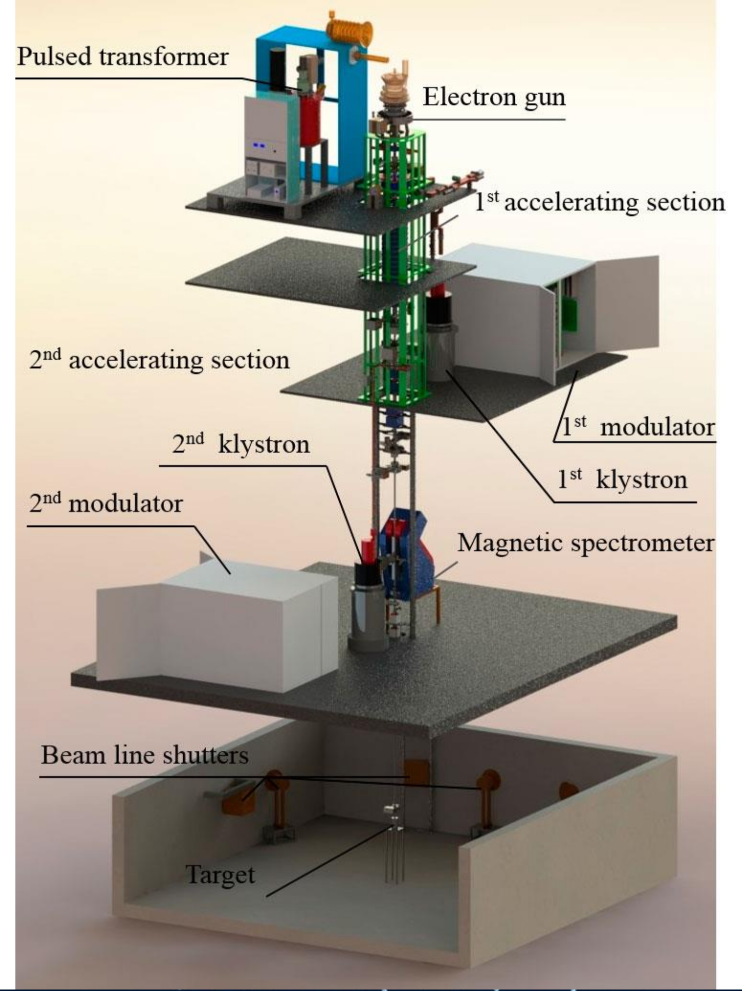
IBR-2 pulsed reactor

Average power, MW	**2**
Peak power, MW	**1850**
Fuel	PuO_2
Number of fuel assemblies	69
Maximum burnup, %	9
Pulse repetiton rate, Hz	5
Pulse half-width, μs	~200
Rotation rate, rev/min • Main reflector • Auxiliary reflector	 600 300
MMR and AMR material	Nickel + steel
MR service life, hours	55 000
Background, %	7
Termal neutron flux density from the surface of the moderator • Time average • Burst maximum	 ~10^{13} n/cm^2 s ~10^{16} n/cm^2 s

IREN facility

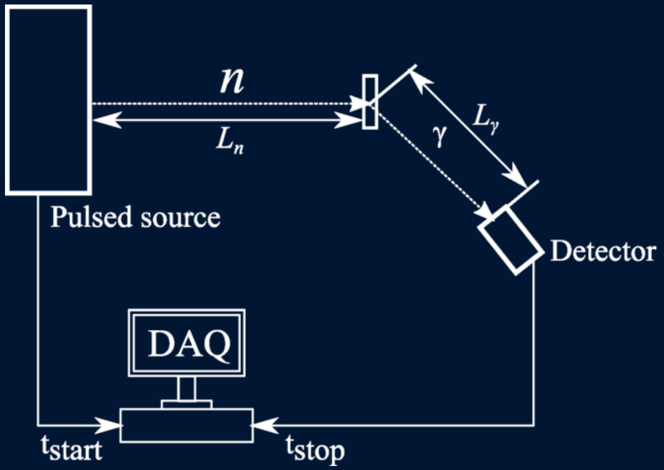
- Current IREN characteristics:
- pulsed electron beam current – 2.0 A
- electron energy – 120 MeV
- pulse width – 100 ns
- repetition rate – 25/50 Hz
- integral neutron yield (3÷5)×10^{11} n/s.
- Neutrons are produced via photonuclear and electronuclear reactions on W target

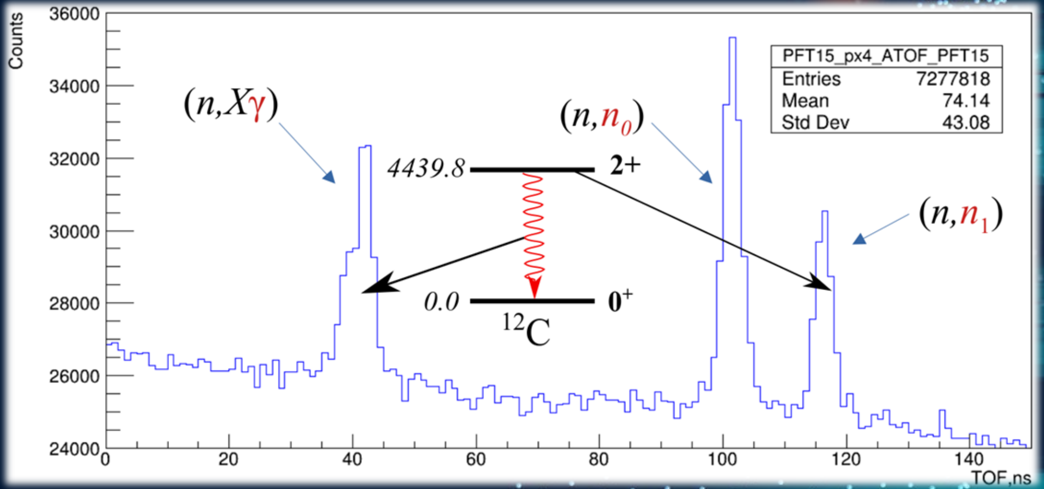




Why pulsed sources?

- It is not easy task to determine neutron energy by measuring energy deposition in detector (like for charged particles/γ)
- Solution: Time-of-flight (TOF) method





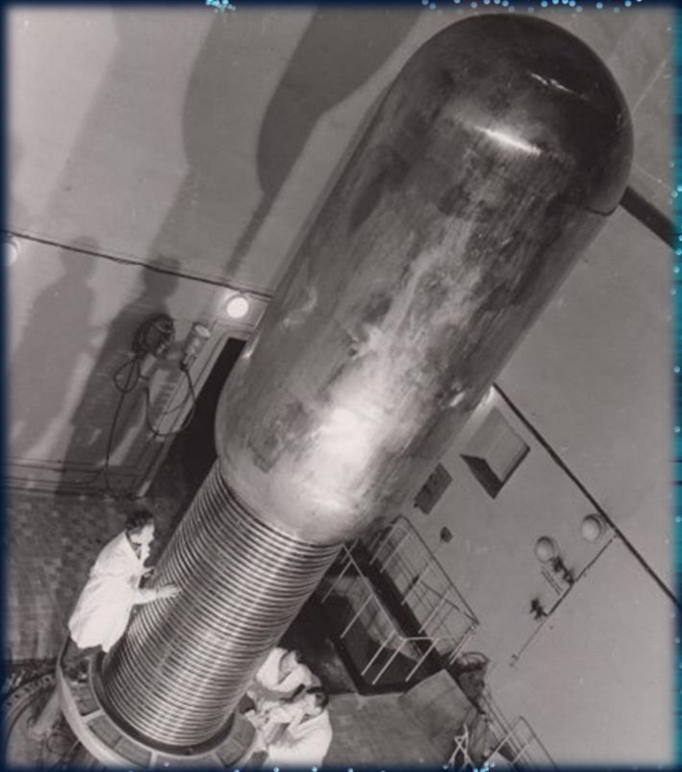
$$T_n = \frac{m_n L_n^2}{2\left(t_{stop} - \frac{L_\gamma}{c} - t_{start}\right)^2}$$

EG-5 facility

1-^{2}H – filled camera, 2-ion guide, 3-beam braker, 4- cooling air guide, 5-pipeline for ^{2}H.

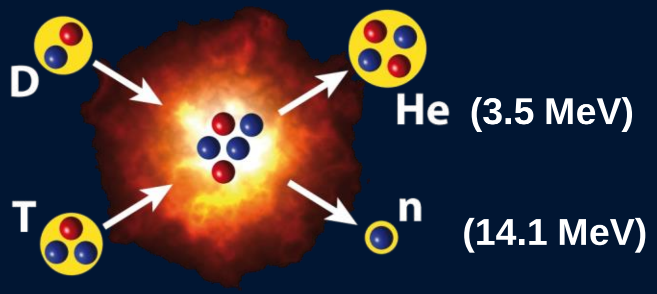
- Beam current up to 100 μA, Energy up to 5 MeV
- Beam energy oscillations <0.01%
- Could be used for any light particles acceleration (*p, d, α*)

More details in A. Kruglyak report



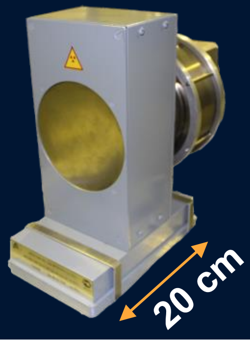
$$^{2}H + ^{2}H \rightarrow n + ^{3}He + 3.27\ \text{MeV}$$

Neutron generators

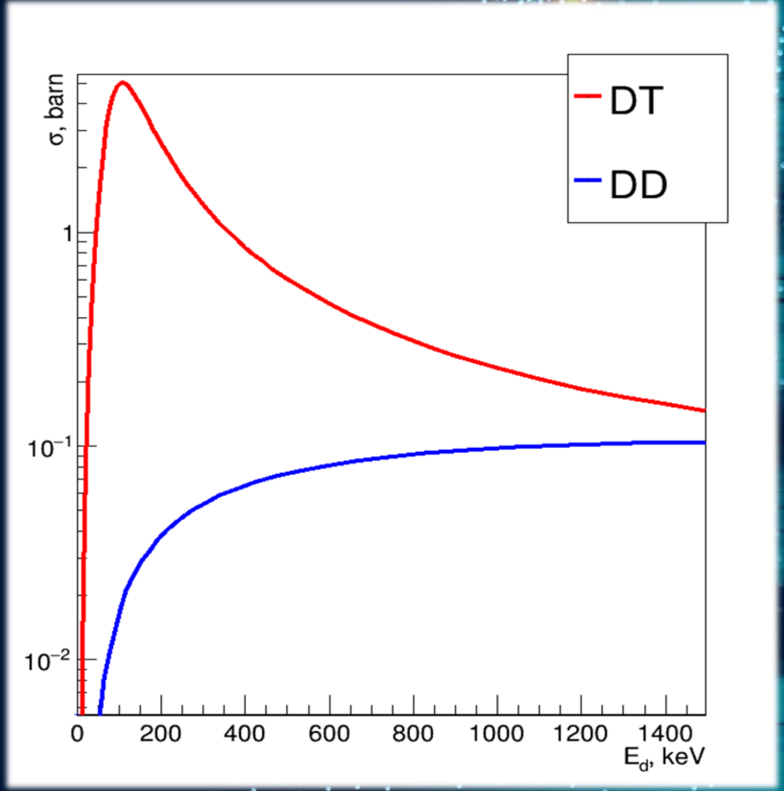


- Very compact neutron sources
- Intensity up to 10^{11} n/sec (pulsed neutron generators)

ING-27



ING-8



Neutron nuclear physics

Fundamentals and applications

Nuclear physics: areas of research

Neutron nuclear physics theme

- Searching for parity violations in nuclear reactions
- Fission physics
- Studying of neutron resonances
- Studying of (n,n'), $(n,2n)$, (n,p) and (n,α) reactions
- Physics of cold and ultracold neutrons, neutron optics
- Applied research:

  Development of new elemental analysis technique

  - Studying of radiation damage
  - Profiling of layered structures

(is not a “neutron” activity)

Two ways in searching of new physics

High energy

High precision

- It is possible to find new effects in low-energy nuclear physics with high-accuracy experiment

Parity violation

- Everything has a wave function. What will happens we will go to a mirror world?

$$\hat{P}:\Psi(\vec{r}) = \hat{P}\Psi(-\vec{r})$$

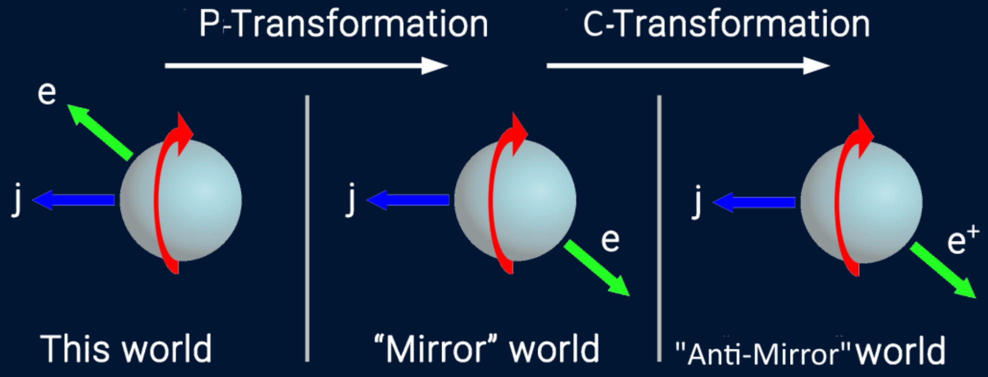
- “Anti” world?

$$\hat{C}:\Psi(\vec{r}) = \hat{C}\overline{\Psi}(\vec{r})$$

- Time-reversed world?

$$\hat{T}:\Psi(\vec{r},t) = \hat{T}\Psi(\vec{r},-t)$$

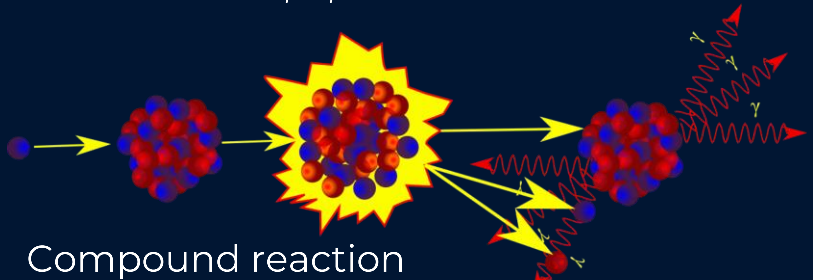
- Weak interaction breaks P,C and CP symmetries (it is possible to distinguish “mirror” world and “anti” world)



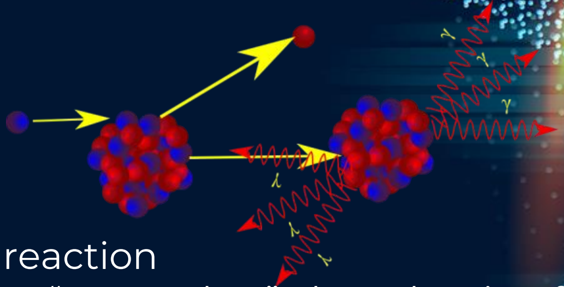
Wu experiment

Parity violation

- Nucleons participate in all known interactions → there **should be** effects of P, C, CP violation in nuclear reactions

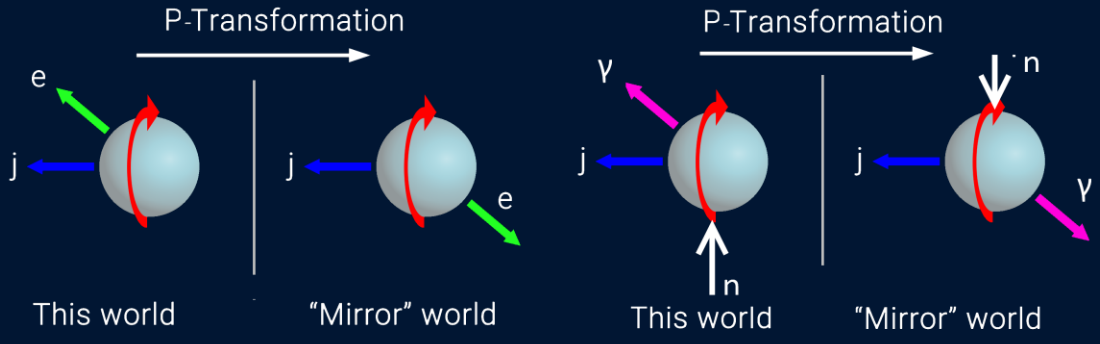


Compound reaction
(nucleus forget about income particle – symmetric angular distribution)



Direct reaction
(nucleus “remember” about begin of reaction-asymmetric angular distribution)

- Searching asymmetry in compound reaction products angular distribution is similar to the Wu experiment

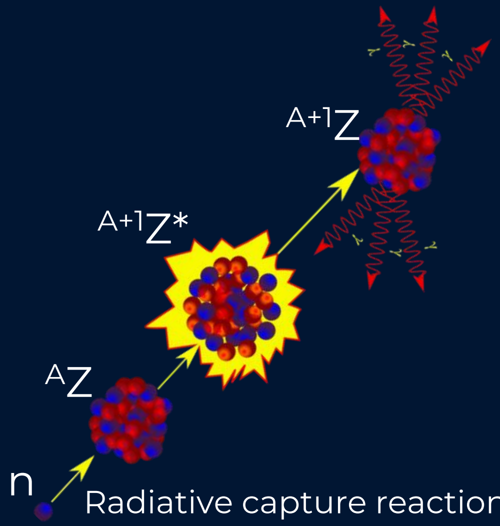


Neutron resonances

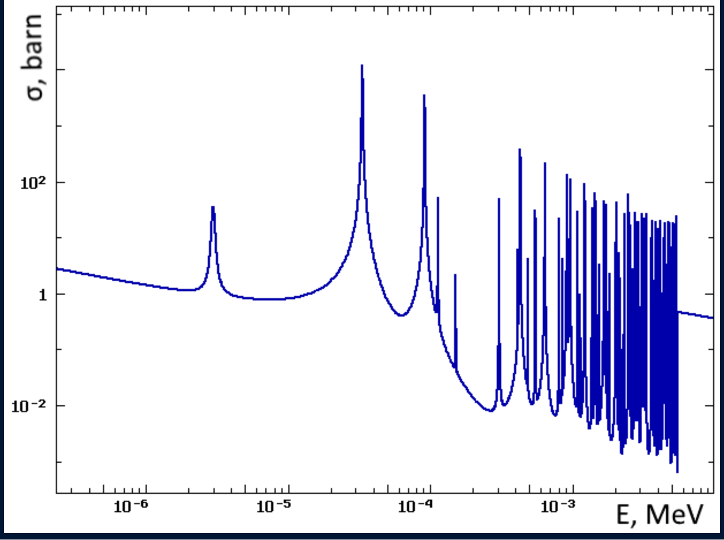
- Nucleus is a quantum system → energetic levels

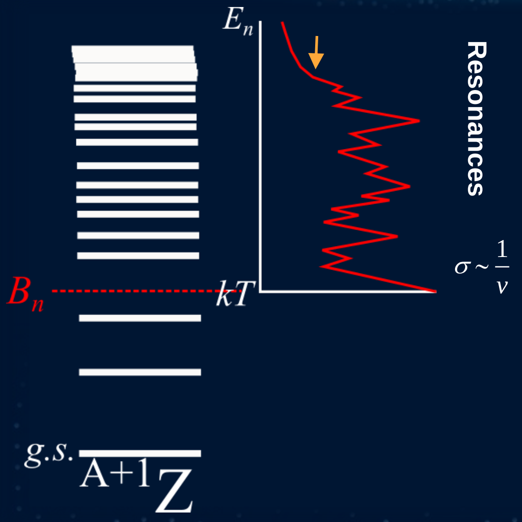
$$^{A}Z(n,\gamma)^{A+1}Z$$

- After neutron capture nucleus excites with energy $E^*=B_n+T_n$
- If B_n+T_n matches ^{A+1}Z energy level, the reaction probability grows dramatically
- It is **compound reaction** → ideal for parity violation search
- Unique tool for studying high excited states properties



Radiative capture reaction

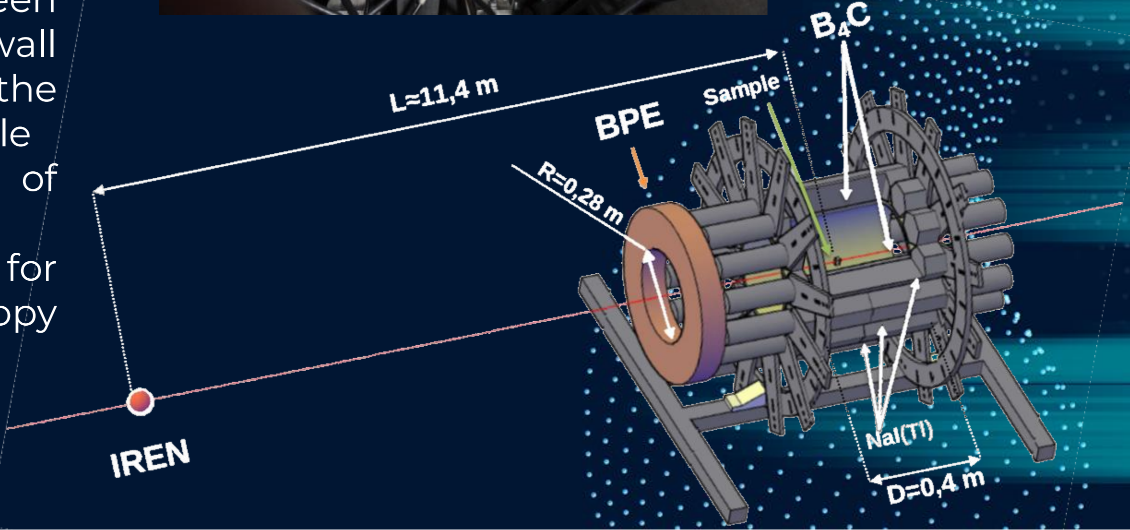




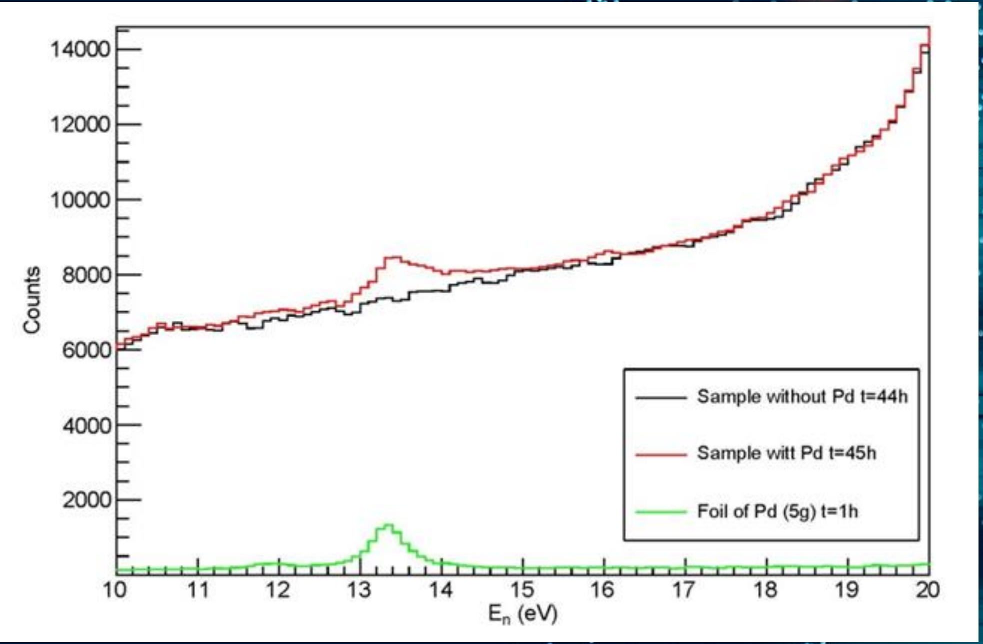
Experimental setup

$$^{A}Z(n,\gamma)^{A+1}Z$$

- “Romashka” gamma-spectrometer: 24 hexagonal NaI(Tl) crystals (78x90x200 mm)
- 10cm-thick Boron polyethylene (BPE) collimator
- B_4C powder of 1cm thickness (ρ=1.8 g/cm3), encapsulated in-between 2 Al cylinders of 0.5 mm wall thickness, was used to capture the neutrons scattered by the sample
- Samples (in the center of “Romashka” system)
- Could be used for forward/backward anisotropy measurement



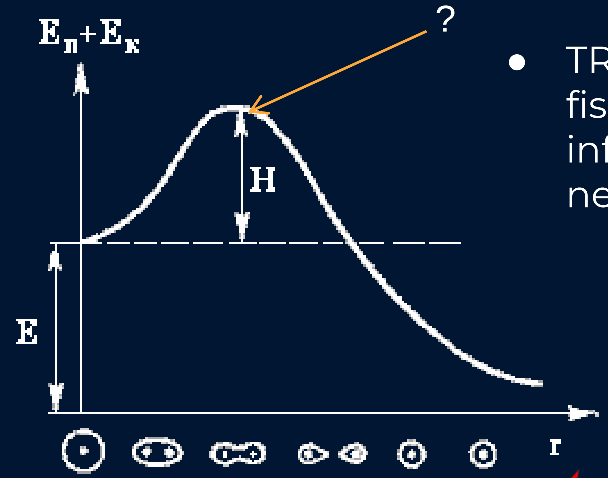
The "Proton" rocket crash



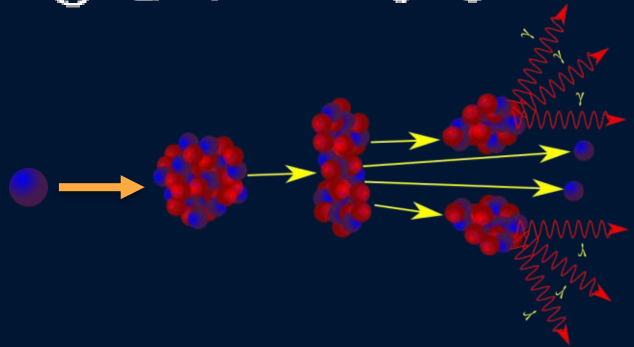
- One hypothesis for crash of the Proton rocket is presence of palladium in some critical components of the engine
- The amount of Pd in the ~60 g sample was found to be 98 ± 10 mg

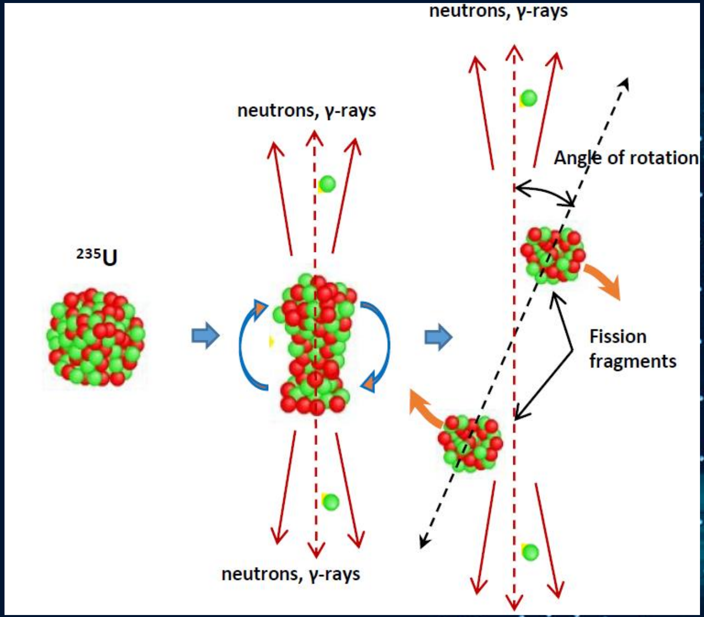
Fission physics

- Fission is well-known process but features of break-up stage are still unclear

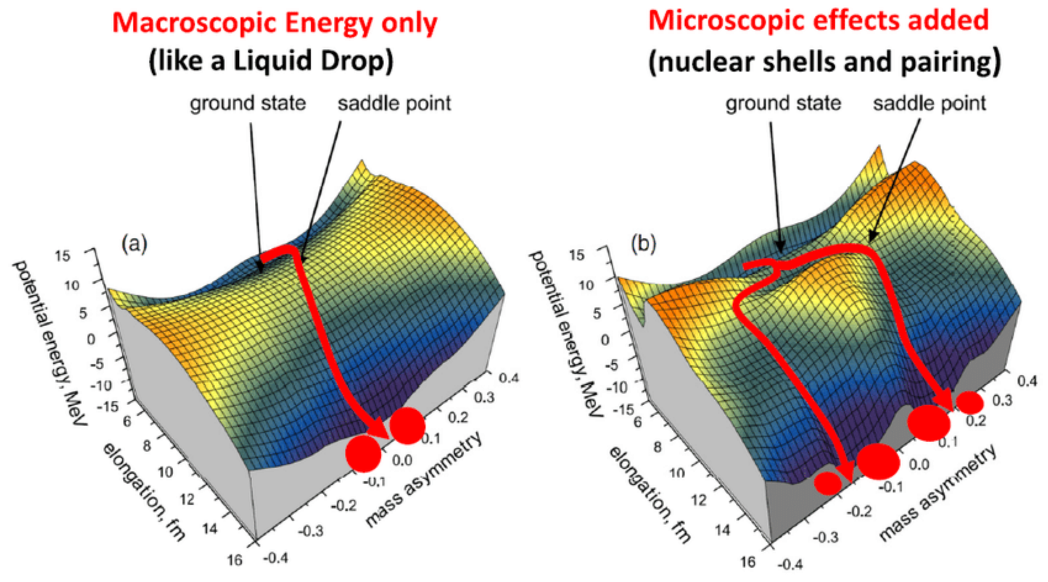


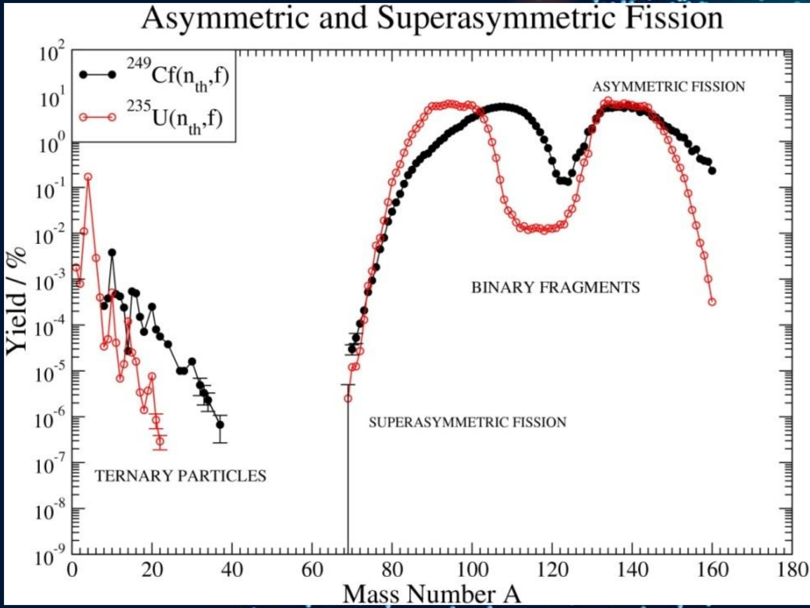
- TRI and ROT effects in angular distributions of fission fragments and/or γ-quanta give information about “total” and “rotation” spin near break-up point





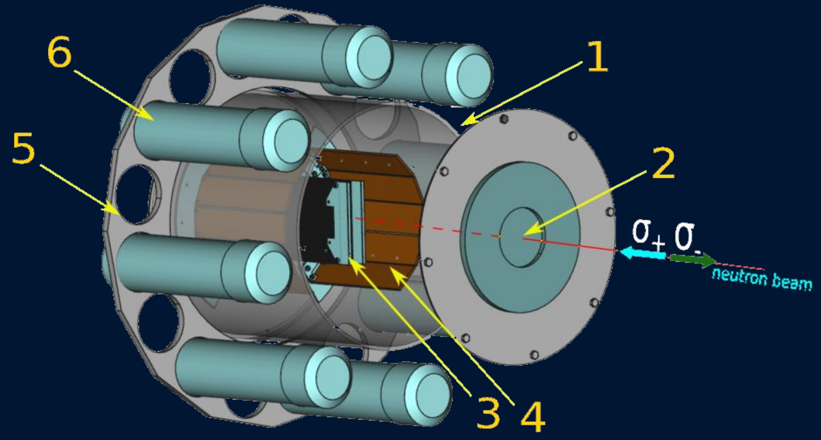
Fission physics





- Rare fission modes provide information about features of the fission barrier

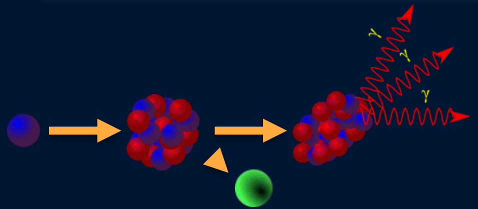
Experimental setups

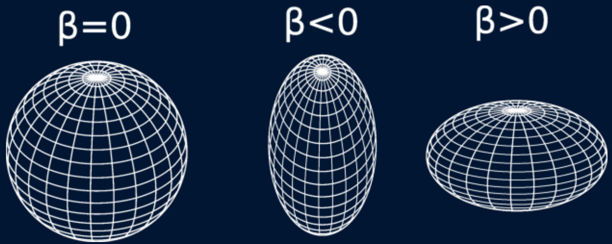


- Experimental setup for studying of fission neutron multiplicity and fragment mass distribution
- To measure mass distribution a position-sensitive ionization chamber is used
- BC501 scintillators are used for neutron registration

- Experimental setup for ROT-effect study
- 1 — fission chamber, 2 — Al input chamber window, 3, 4 — fission fragment detectors based on position-sensitive multiwire proportional counters (start and stop detectors), 5 — holder, 6 — scintillation plastic detectors of γ-quanta and neutrons
- Angular distributions of γ-quanta, neutrons and fission products are measured

Studying of neutron-induced reactions





- Optical model

$$U(r,E) = -\mathcal{V}_V(R,r,E) - i\mathcal{W}_V(R,r,E) -$$
$$-i\mathcal{W}_D(R,r,E) + (R,\vec{l}\cdot\vec{\sigma})\times$$
$$\times\left(\mathcal{V}_{SO}(R,r,E) + i\mathcal{W}_{SO}(R,r,E)\right)$$

$$R = R_{\kappa 0}\left(1+\sum_{\lambda}\beta_\lambda Y_\lambda(\theta,\phi)\right), \quad R = R_{\kappa 0}\left(1+\sum_{\lambda\mu}\alpha_{\lambda\mu} Y_{\lambda\mu}(\theta,\phi)\right),$$

Oscillator

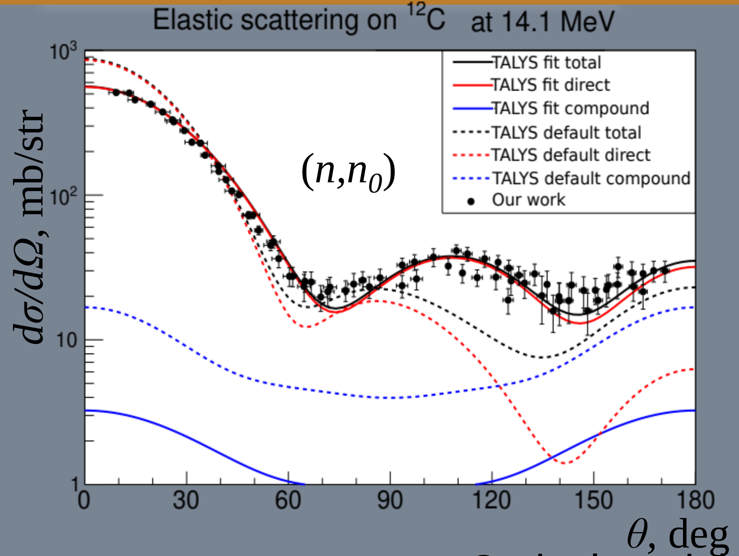
Rotator

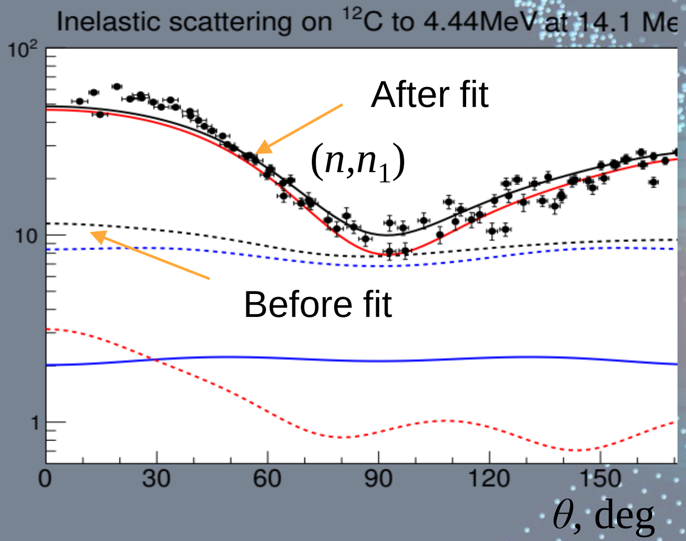
^{A}Z
Levels at same distance

^{A}Z
Levels grows as ΔE^2

- (*n,n'*), (*n,2n*), (*n,p*) and (*n,α*) reactions is a unique tool for nuclear structure and shape investigation
- Data needed to adjust parameters models for astrophysical calculations
- Acquiring more accurate data for applied research

Studying of neutron-induced reactions

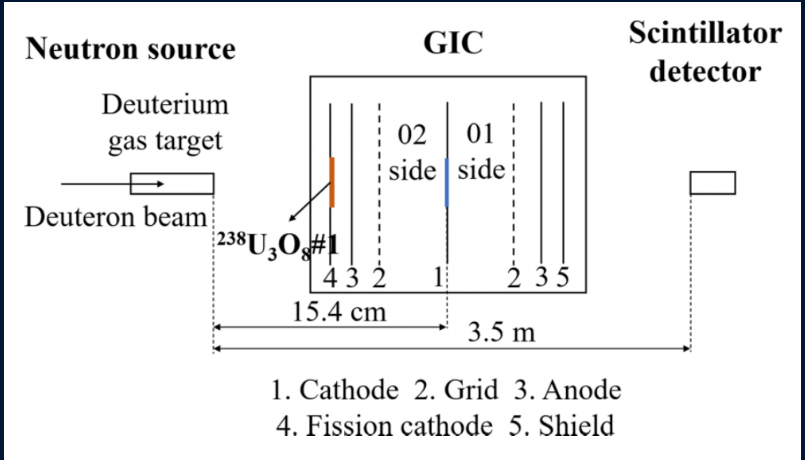


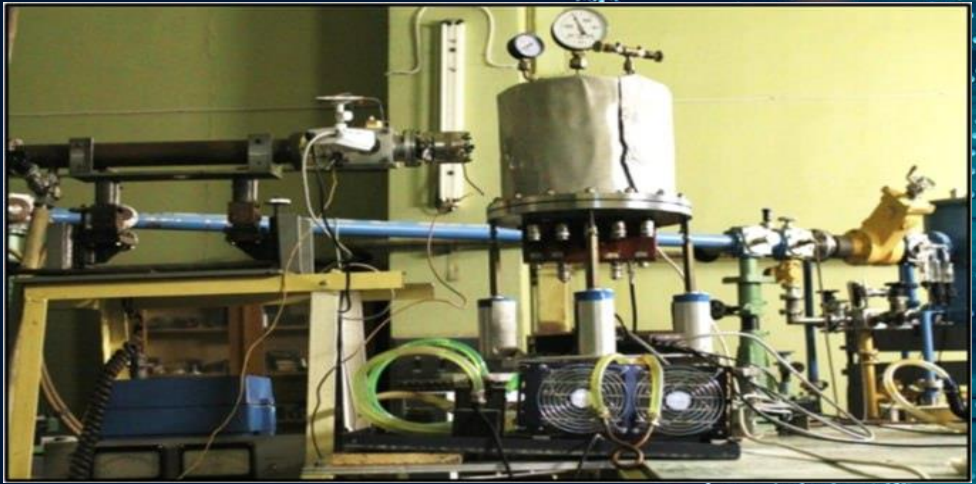


Optical model fit for $^{12}C(n,n')$.

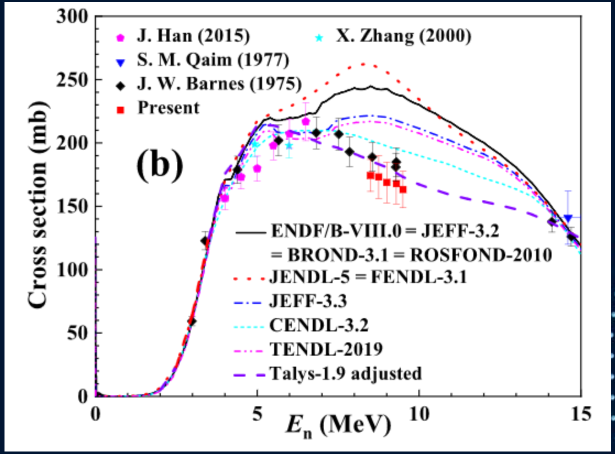
Source	Approach	V_V MeV	W_V MeV	r_V fm	a_V fm	W_D MeV	r_D fm	a_D fm	V_{SO} MeV	W_{SO} MeV	r_{SO} fm	a_{SO} fm	β_2	χ^2/N
Default calc.	DWBA	49.07	1.26	1.13	0.68	7.65	1.31	0.54	5.39	-0.07	0.90	0.59	**0.40**	73.5
Our data fit	CC rot.	49.78	0.03	1.05	0.51	3.74	1.27	0.31	7.79	-3.38	1.00	0.55	**-0.95**	2.49
Other data fit	CC rot.	49.73	0.21	1.11	0.44	5.42	1.20	0.34	6.31	-3.75	1.21	0.59	**-0.83**	2.72

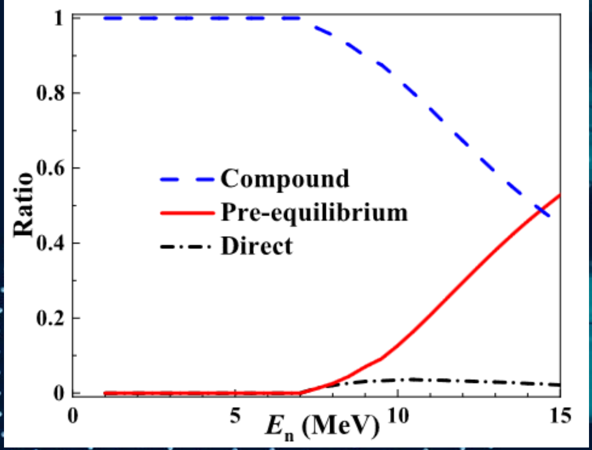
Experimental setups



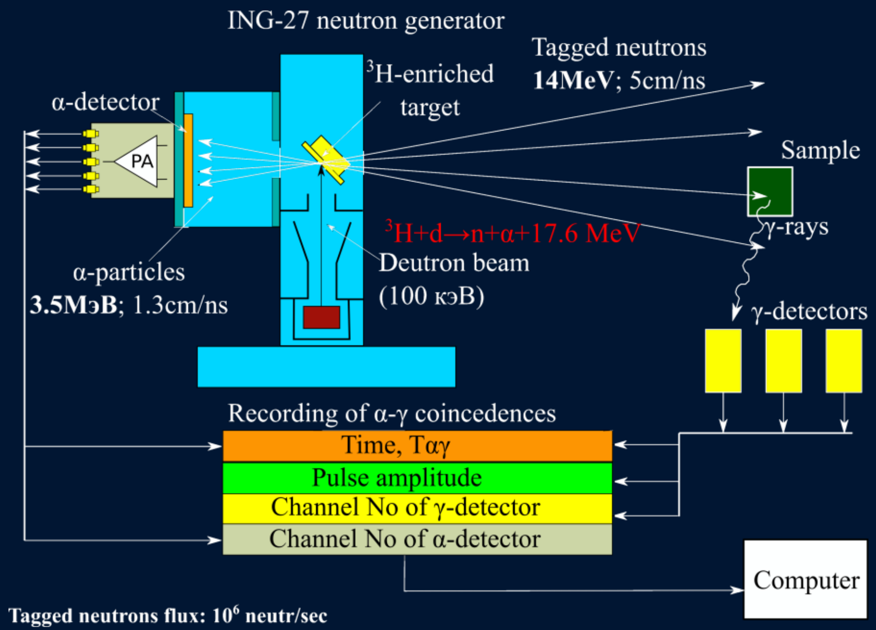


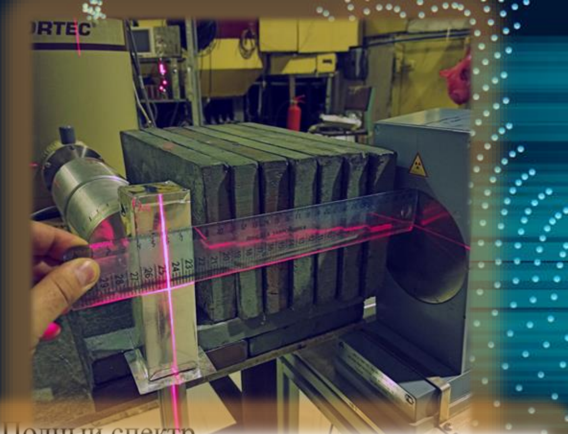
- Experimental setup for (n,α) investigation
- ion. chamber is used to measure energies of α
- ^{238}U for neutron fluence monitoring, n-detector for measurement of n-energy
- Estimation of nuclear reaction mechanisms impacts in result

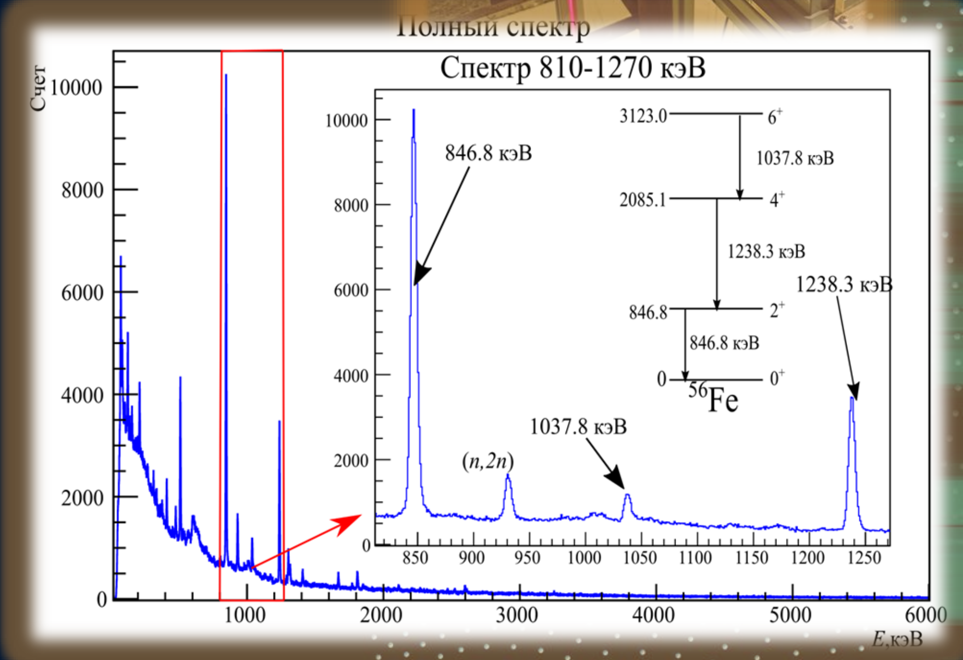




Experimental setups

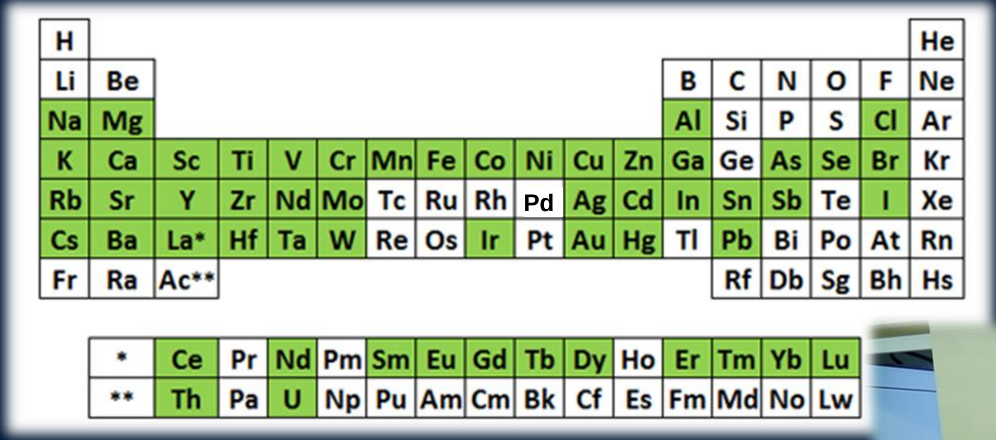






- Application of the Tagged neutron method improves peak/background ratio
- It is possible to determine all 3 spatial coordinates of reaction
- With proper γ-ray database could be used in inspection complexes

Applied research



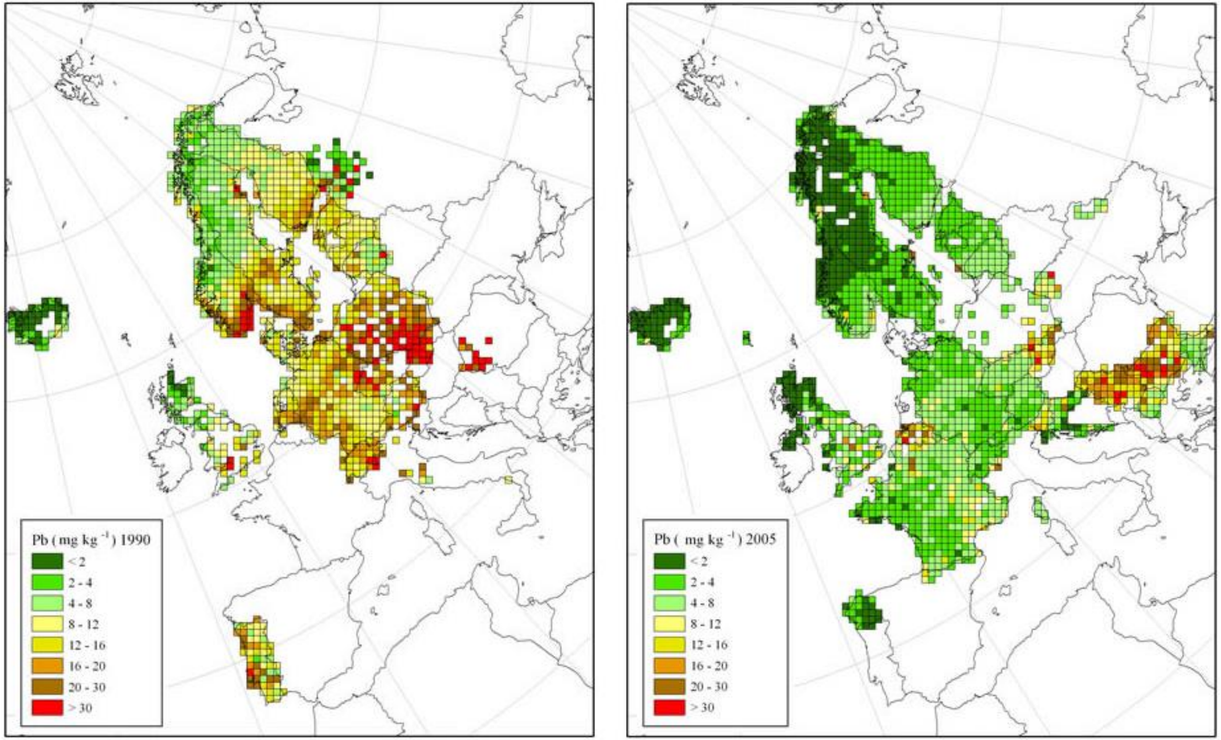
- Neutron activation analysis is a very sensitive (ppb) method of elemental analysis based on $^{A}Z(n,\gamma)$ – products measurement
- In FLNP this method is implemented in REGATA project

The Main Areas of Research

- Quality control of the air (study of aerosol filters, biomonitoring with mosses, lichens, etc.)
- Assessment of terrestrial and aquatic ecosystems (soil, sediments, biota)
- Geology and Geoecology
- Foodstuffs
- Materials Science (new and ultra–pure materials, new technologies)
- Biotechnology (development of new medicines and sorbents)
- Archaeology

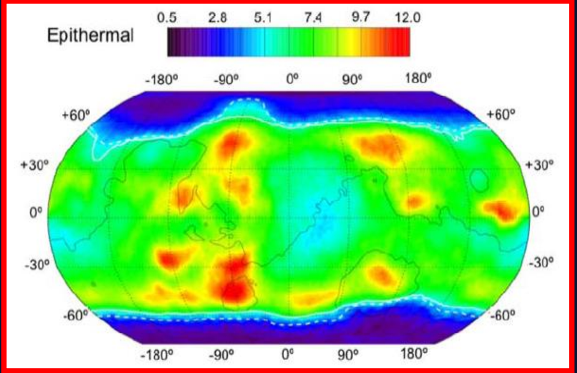
Applied research

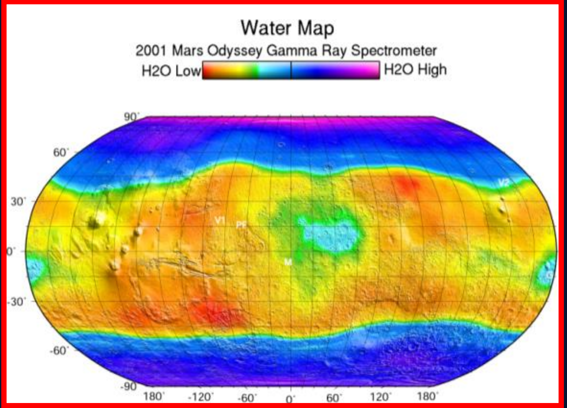
- Mosses are very good absorbers of pollutants from air
- They have no roots!
- Easy for harvesting and sample preparation
- See https://moss.jinr.ru

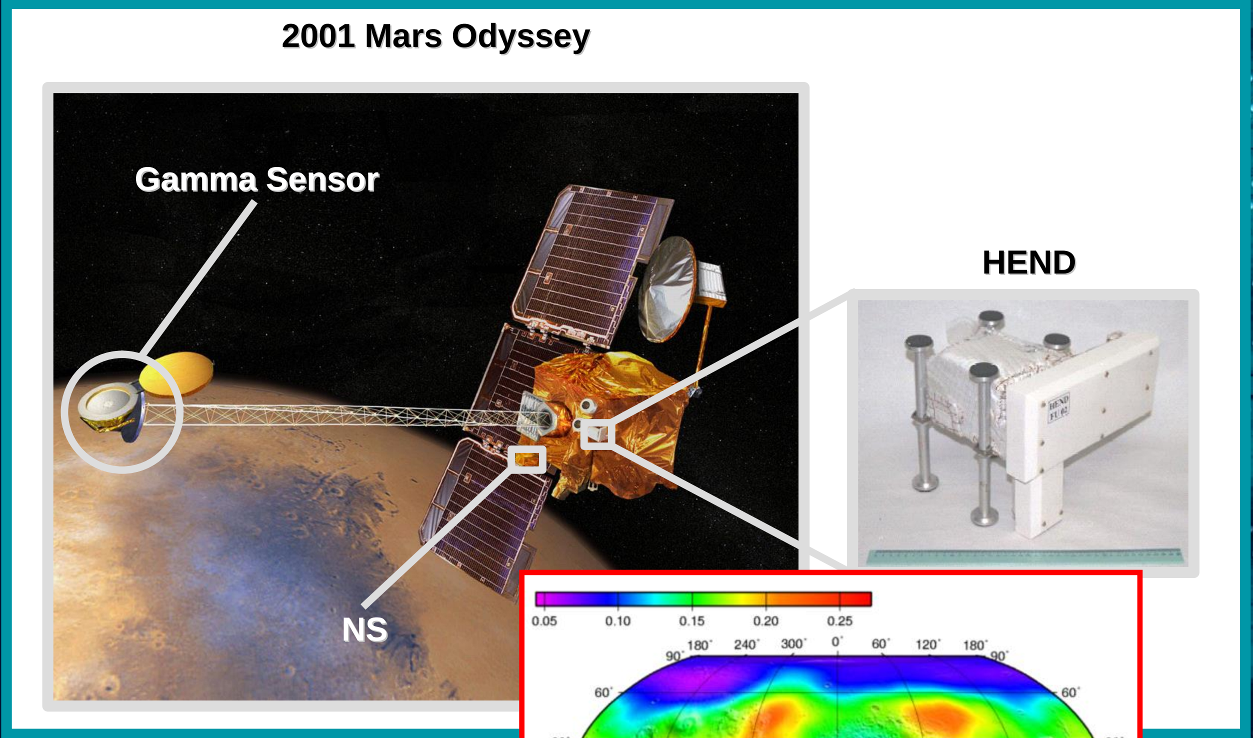


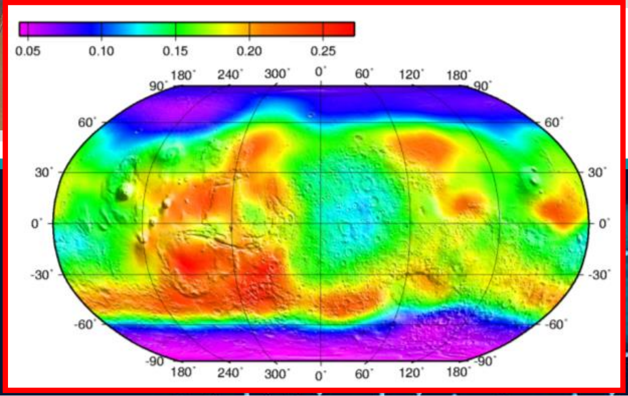
Mean lead concentration in mosses per 50 x 50 km2 grid in 1990 and 2005 respectively.

Neutrons in space

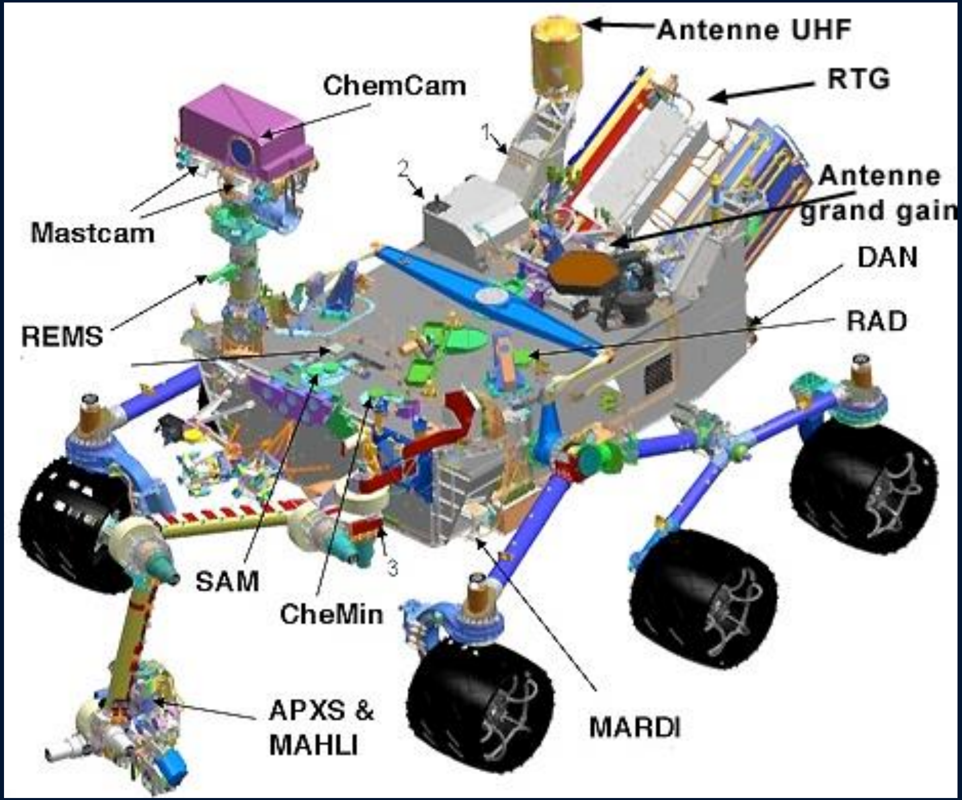


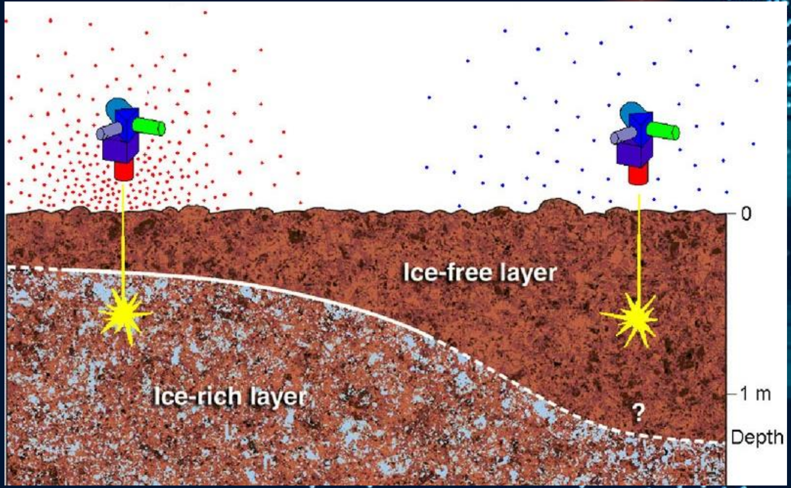






Neutrons in space

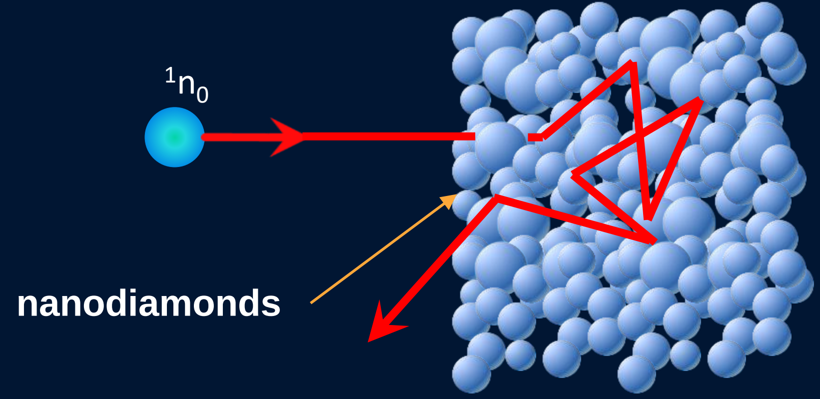




- Water is slowing down the neutrons therefore it is possible to estimate its concentration via neutron spectra measurement

Cold neutrons and neutron optics

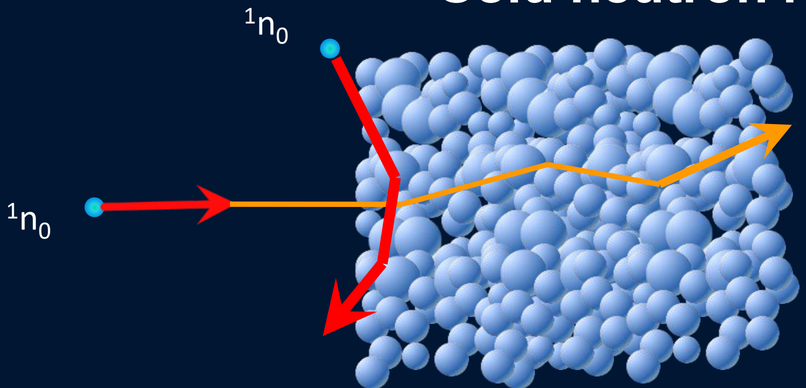
Very cold neutron reflector (E<10^{-4} eV, λ>30 Å)



- Large scattering probability
- Large scattering angle
- Small penetration

Possible to have an efficient reflector at any incident angle

Cold neutron reflector (E<5·10^{-3} eV, λ>4 Å)

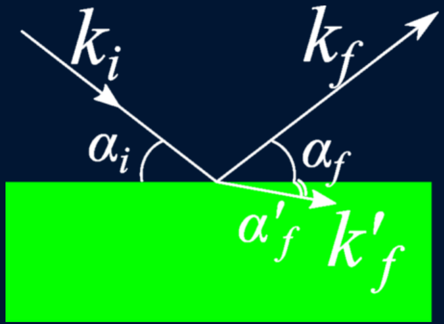


- Small scattering probability
- Small scattering angle
- Deep penetration

Possible to have an efficient reflector only at gliding angle of neutron incidence

Cold neutrons and neutron optics

- λ of cold and ultracold neutrons is large enough for scattering on nano-dimensional objects like nanoparticles and crystal lattice
- It is even possible to store them in the bottle
  - To measure neutron lifetime and dipole moment
  - Study gravitational properties
  - Check neutron optics



- Neutrons could be reflected as light
- Critical angle α for full reflection:

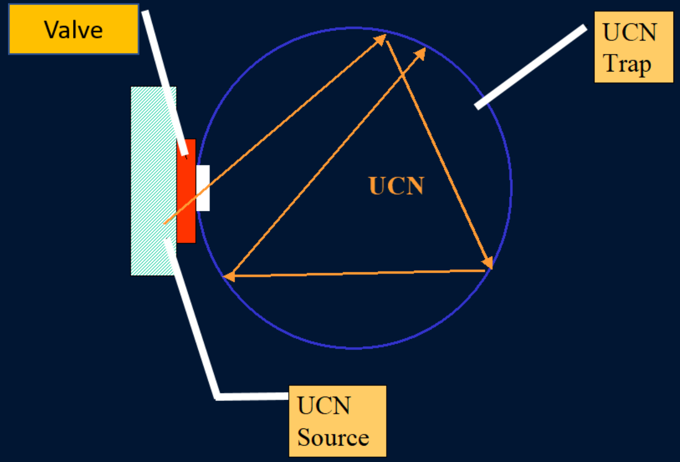
$$\cos\alpha = n;$$

$$n = 1 - \frac{\lambda^2 N\langle b\rangle}{\pi}$$

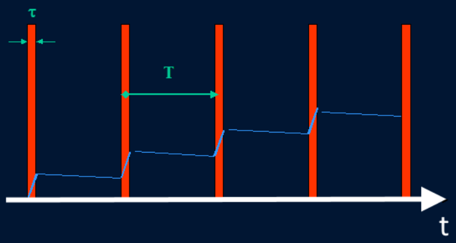
- N-concentration of atoms
- b-scattering length

$$\frac{d\sigma}{d\Omega} = |b^2|$$

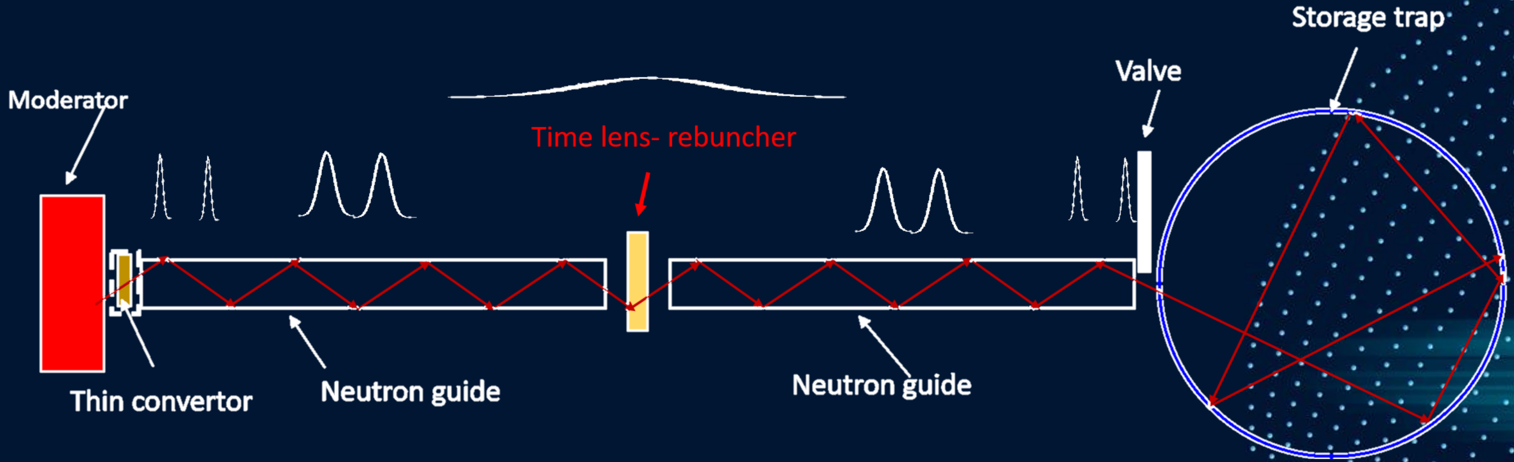
Cold neutrons and neutron optics



- Idea of UCN source



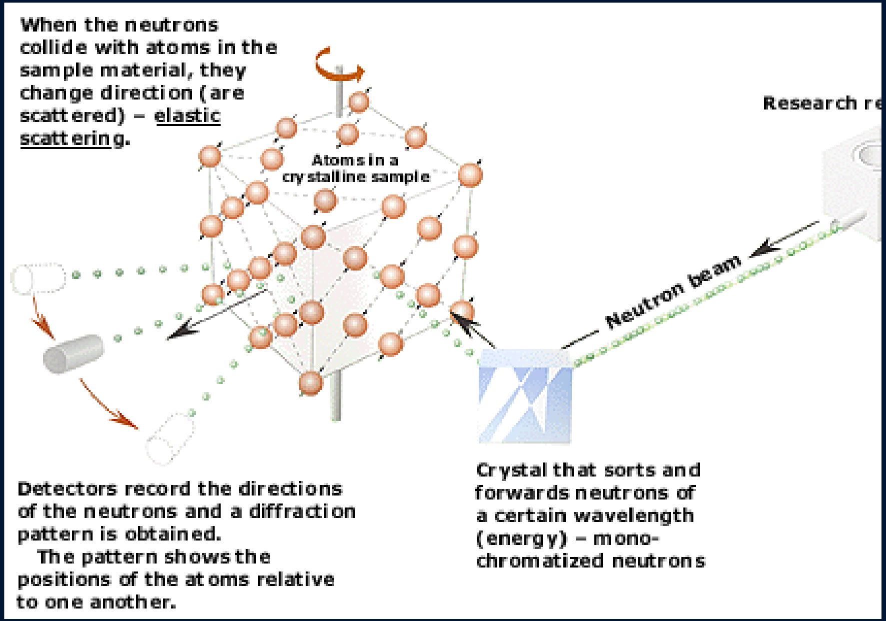
- Possible realization

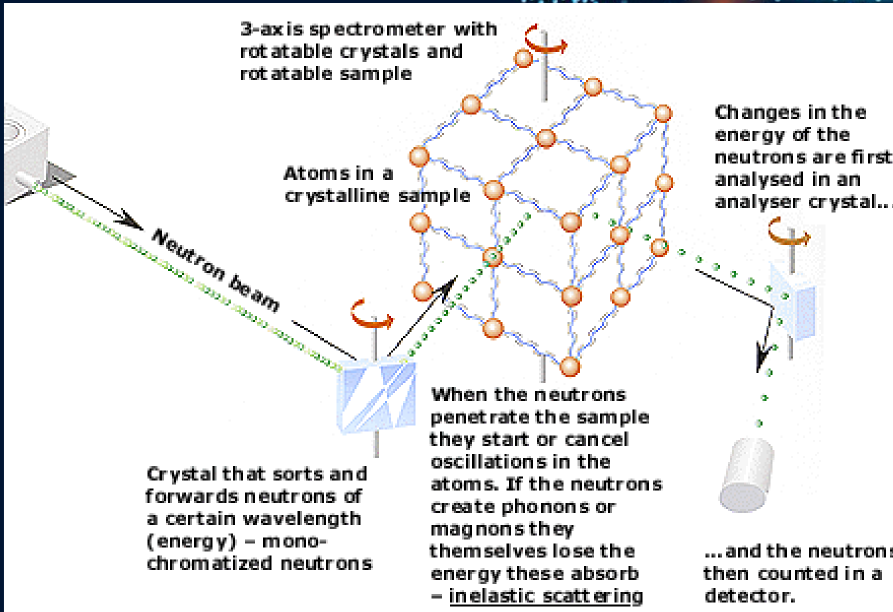


Condensed matter physics

Fundamentals and applications

Why neutrons?





- Thermal neutrons **wavelength** is close to characteristic interatomic distances in crystals (~2 A):
- **good for structural investigations via elastic scattering**

- Thermal neutrons **energy** is close to characteristic energies of atomic excitations (~0.02 eV):
- **good for lattice dynamics investigations via inelastic scattering**

Scattering potential

$$V(\vec{r}) = \frac{h^2}{2\pi m \sum b_i \delta(\vec{r} - \overrightarrow{R_i})} + (\overrightarrow{\mu_n} \vec{B}(\vec{r}))$$

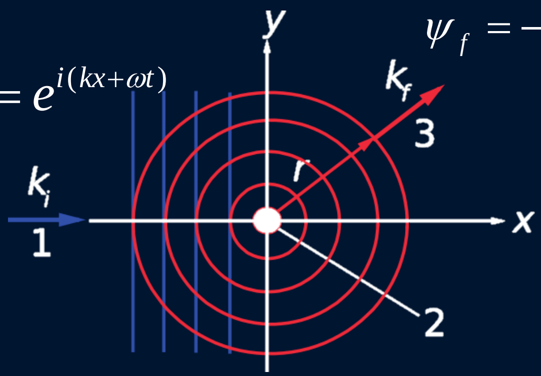
Magnetic potential

Fermi potential (includes short range of nuclear forces, assuming b(E)=const)

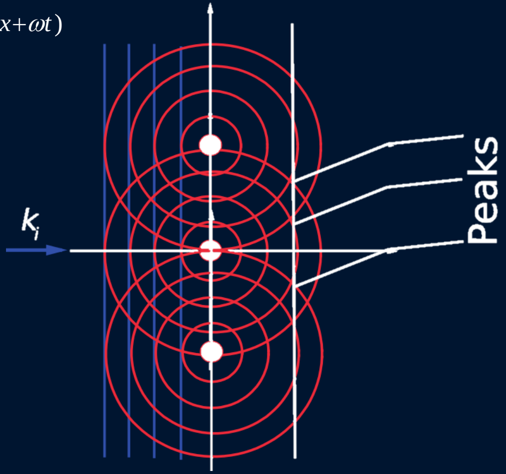
$$\sigma = 4\pi \, | \, b^2 \, |$$

$$\psi_f = -\frac{b}{r} e^{i(kx+\omega t)}$$

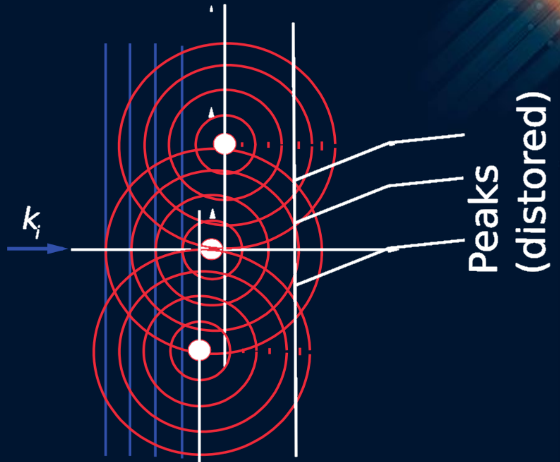
$$\psi_i = e^{i(kx+\omega t)}$$



$$\left(-\frac{\hbar^2}{2m} \Delta + V \right) \Psi = E\Psi$$



Coherent scattering (same phase)

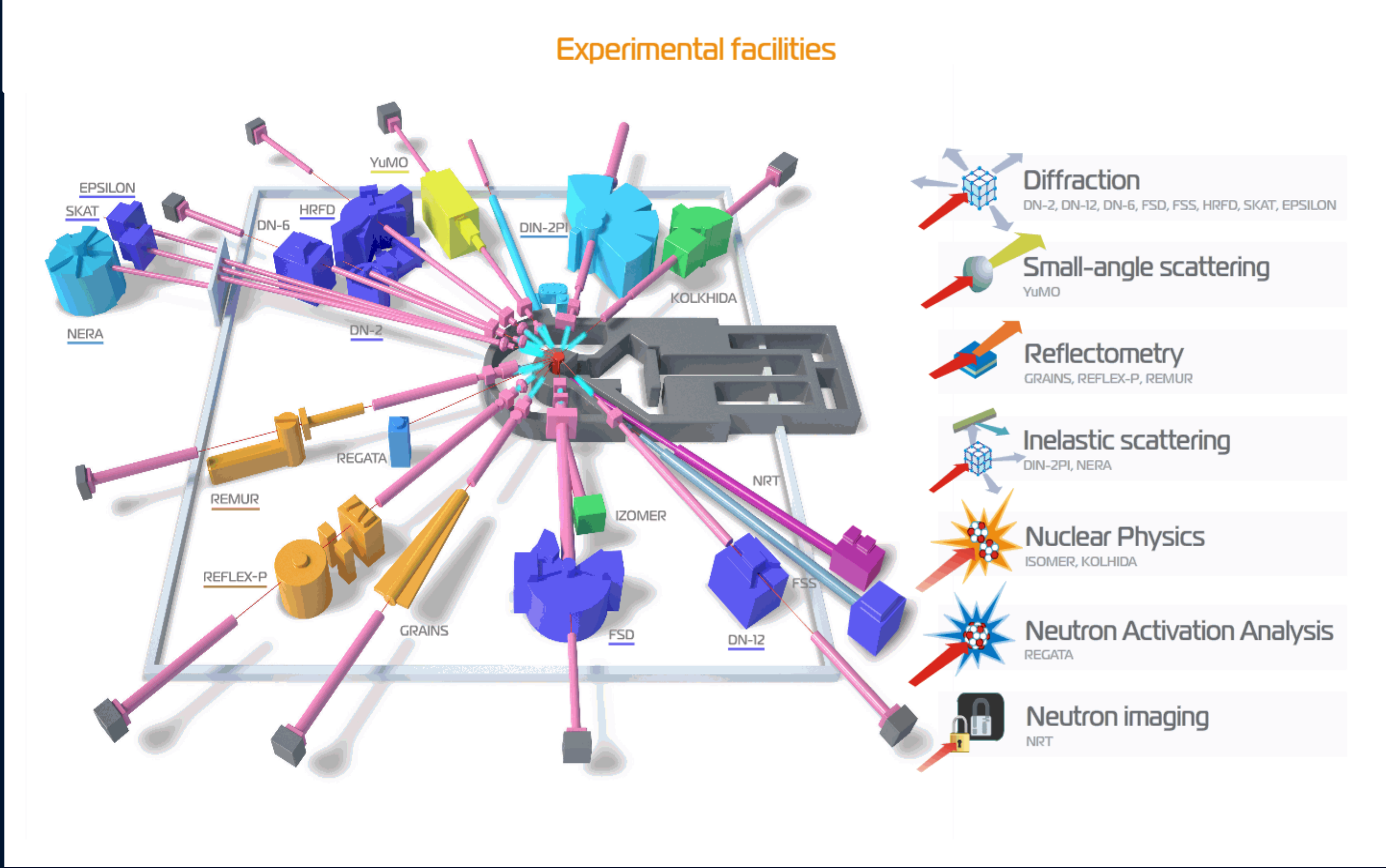


Incoherent scattering (distorted phase)

Methods

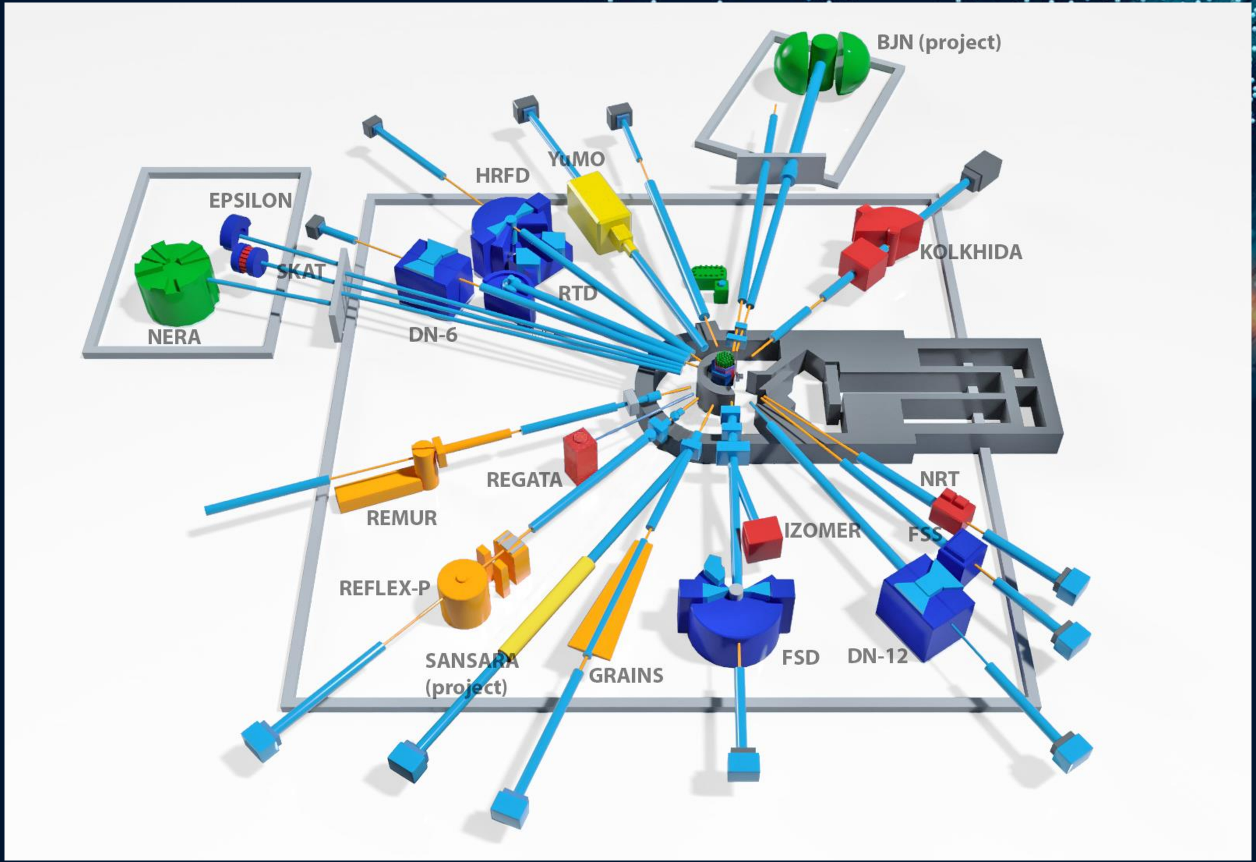
- Diffraction
  - Crystal structure
  - Magnetic structure
  - Phase structure
- Small-angle scattering
  - Structure of nanoparticles in solutions
  - Structure of biomembranes
- Reflectometry
  - Layered structures
  - Surface properties
  - Magnetic structure
- Inelastic scattering
  - Molecular and crystal dynamic
- Neutron imaging

Facilities (now)

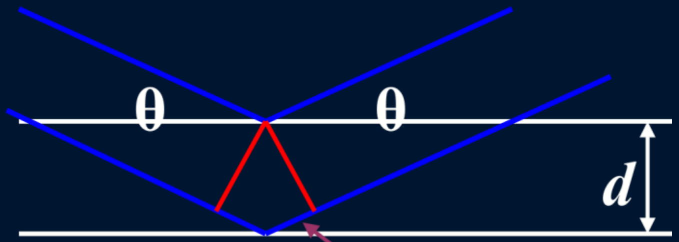


Facilities (in future)

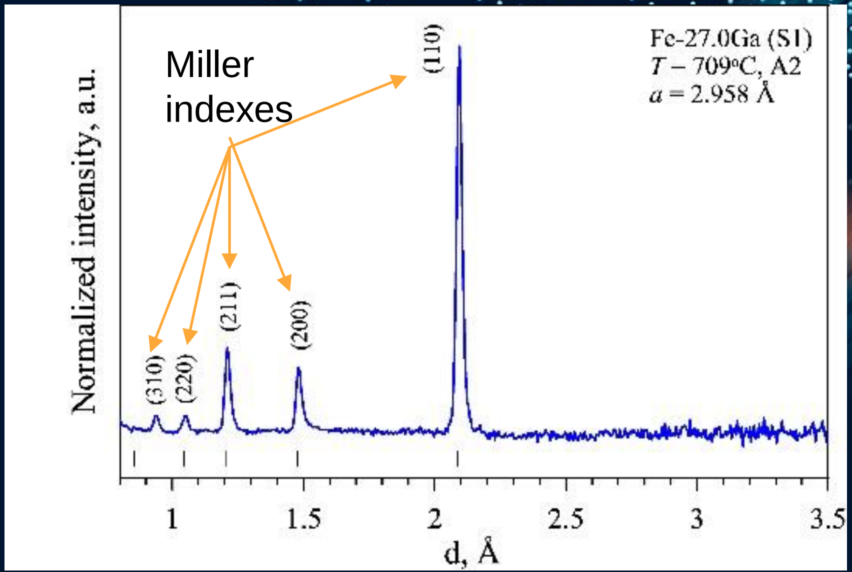
- BJN-inelastic scattering (improving geometry and apparatus)
- SANSARA-small-angle scattering combined with neutron radiography and application of cold moderators



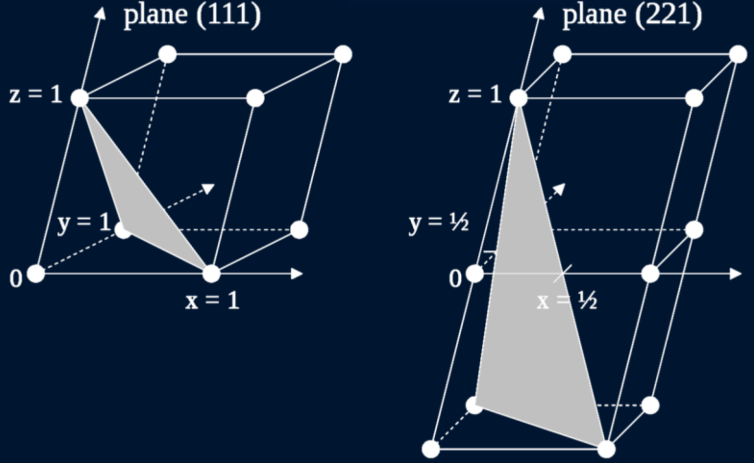
Diffraction

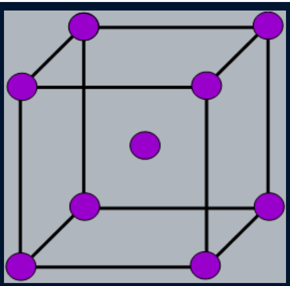


- Bragg law



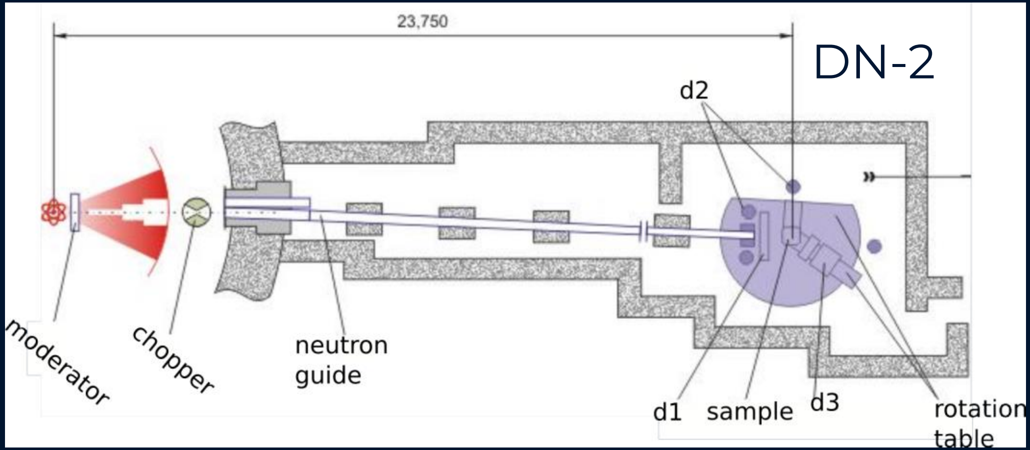
$$2d \sin \theta = n\lambda$$

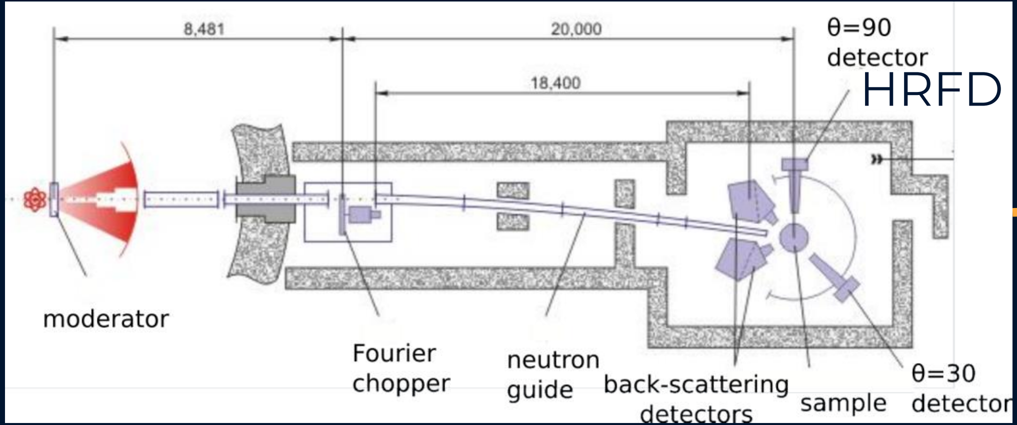




- Miller indexes define lattice plains

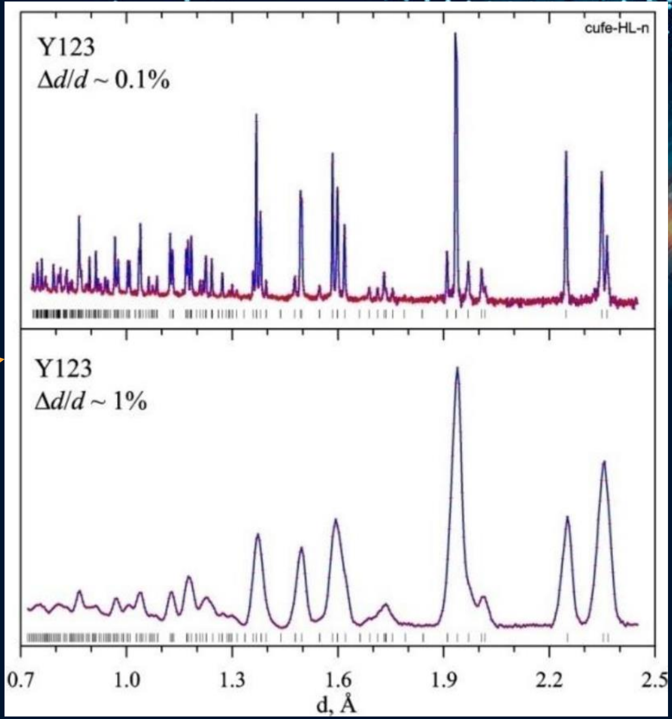
Diffraction





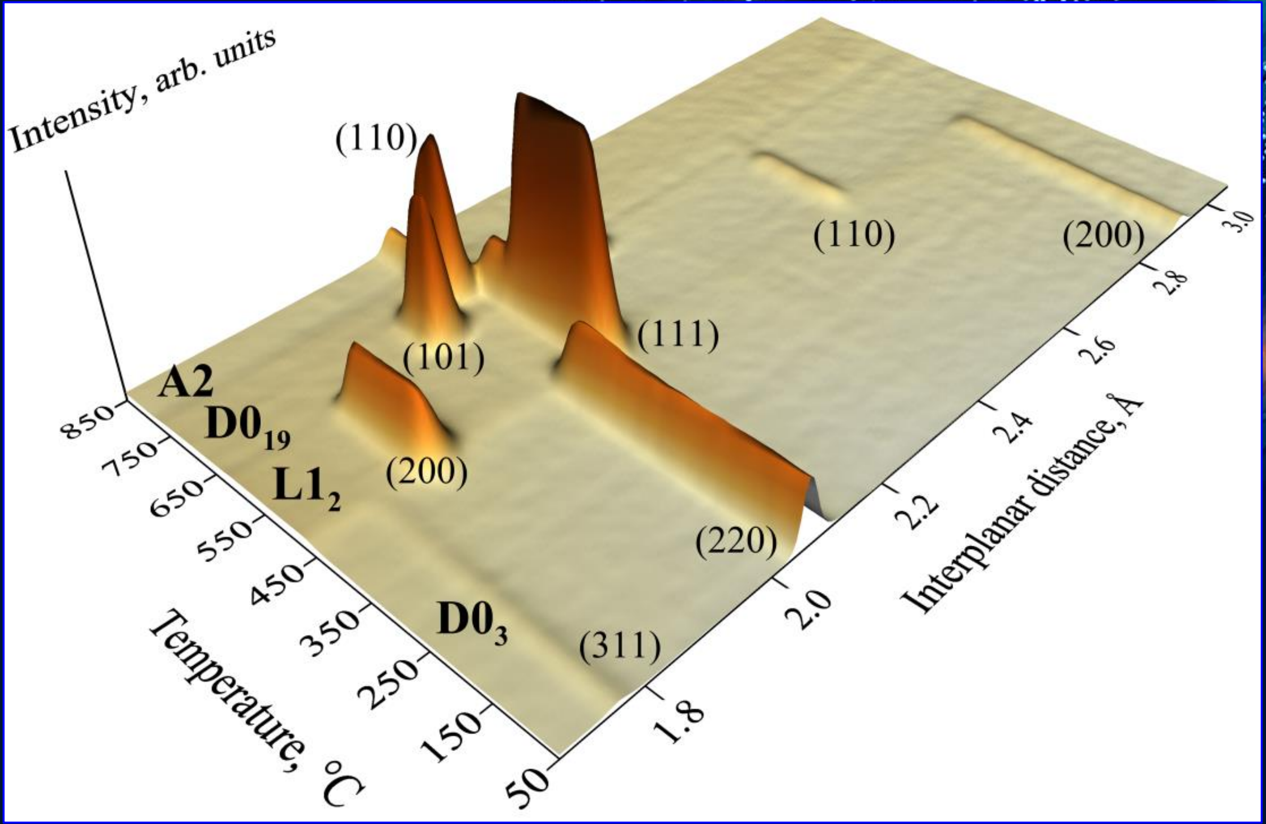
TOF-difractometer→fixed θ

$$2d\sin\theta = n\lambda$$



Diffraction

- Diffractogram of the Fe-Ga alloy with giant magnetostriction effect
- Phase transitions data is needed to optimize the mixture



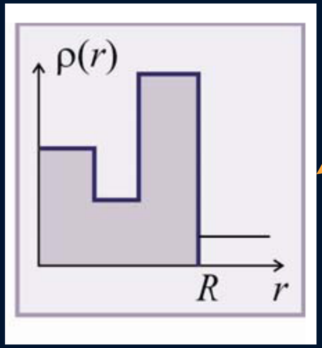
- Phase transitions ↔ changes in crystal lattice pattern

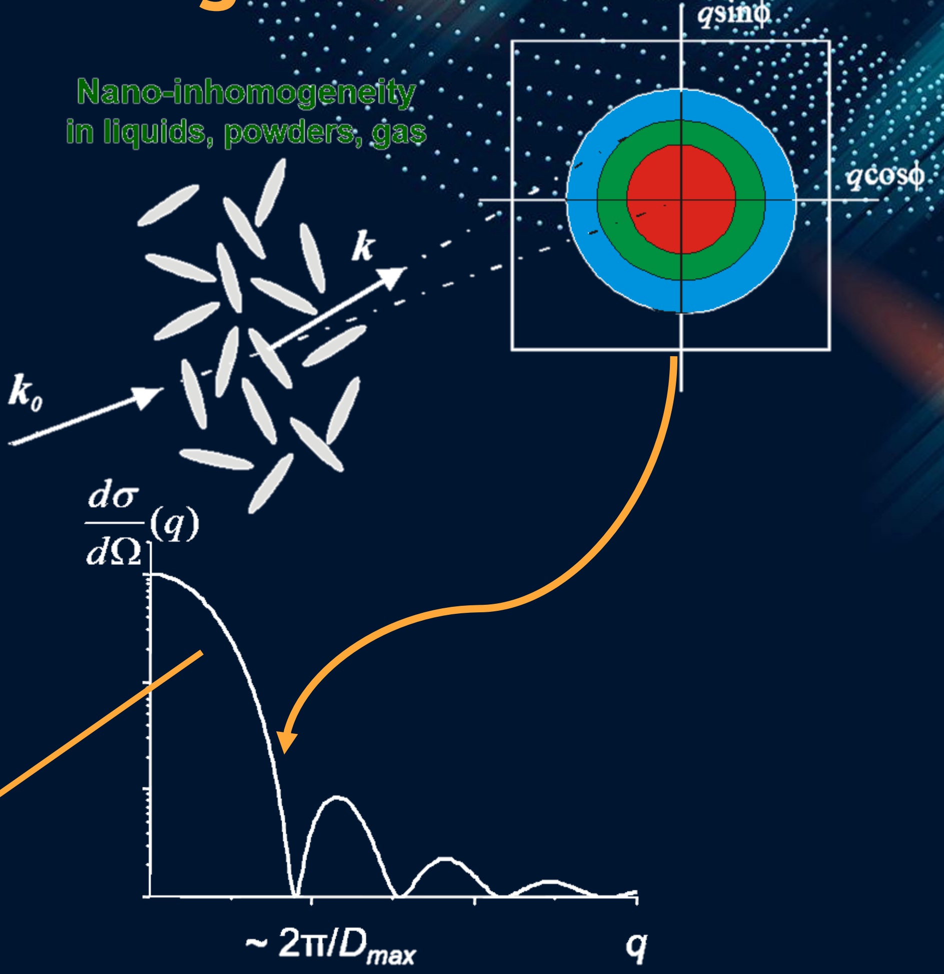
Small-angle neutron scattering

- Neutron scattering on particles with λ≫R leads to beam broadening
- Process is going on many-atomic structures → density of scattering lengths $\rho(r)$ is used instead b for crystals

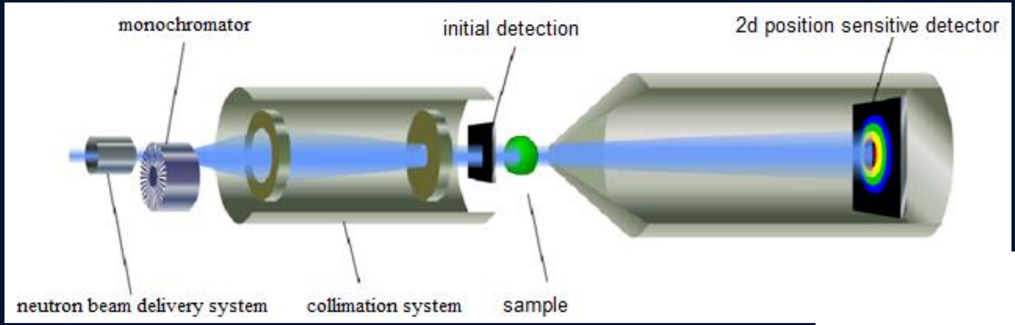
$$\vec{q} = \vec{k} - \vec{k_0}; q = \frac{4\pi}{\lambda}\sin\frac{\theta}{2}$$

$$\frac{d\sigma}{d\Omega} = \int_V \int_V \rho(\vec{r_1})\rho(\vec{r_2}) e^{i(\vec{q},\vec{r_1}-\vec{r_2})} d\vec{r_1} d\vec{r_2}$$



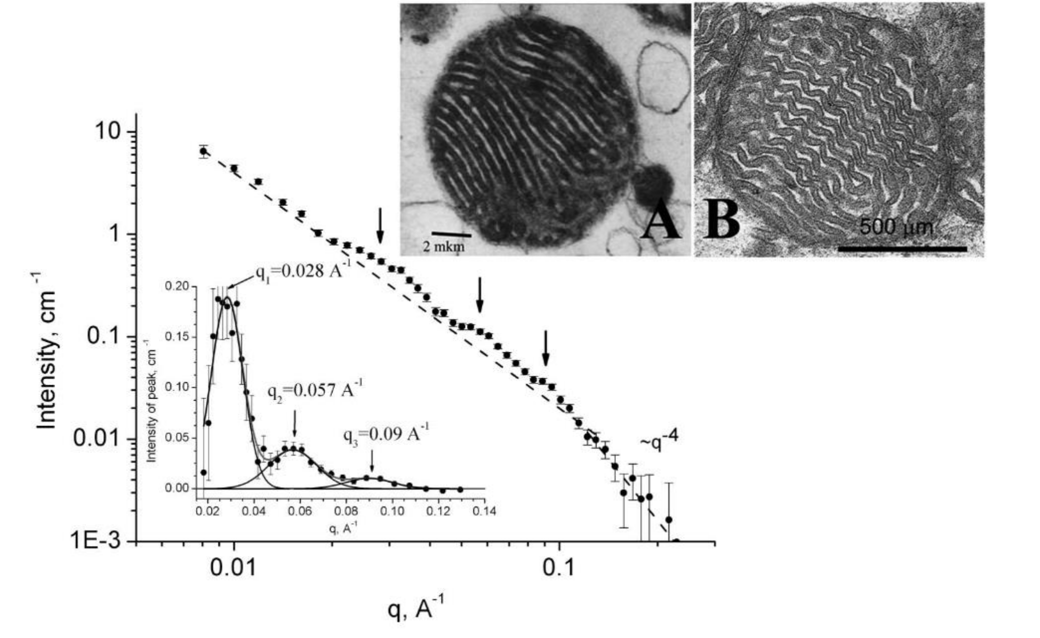


Small-angle neutron scattering

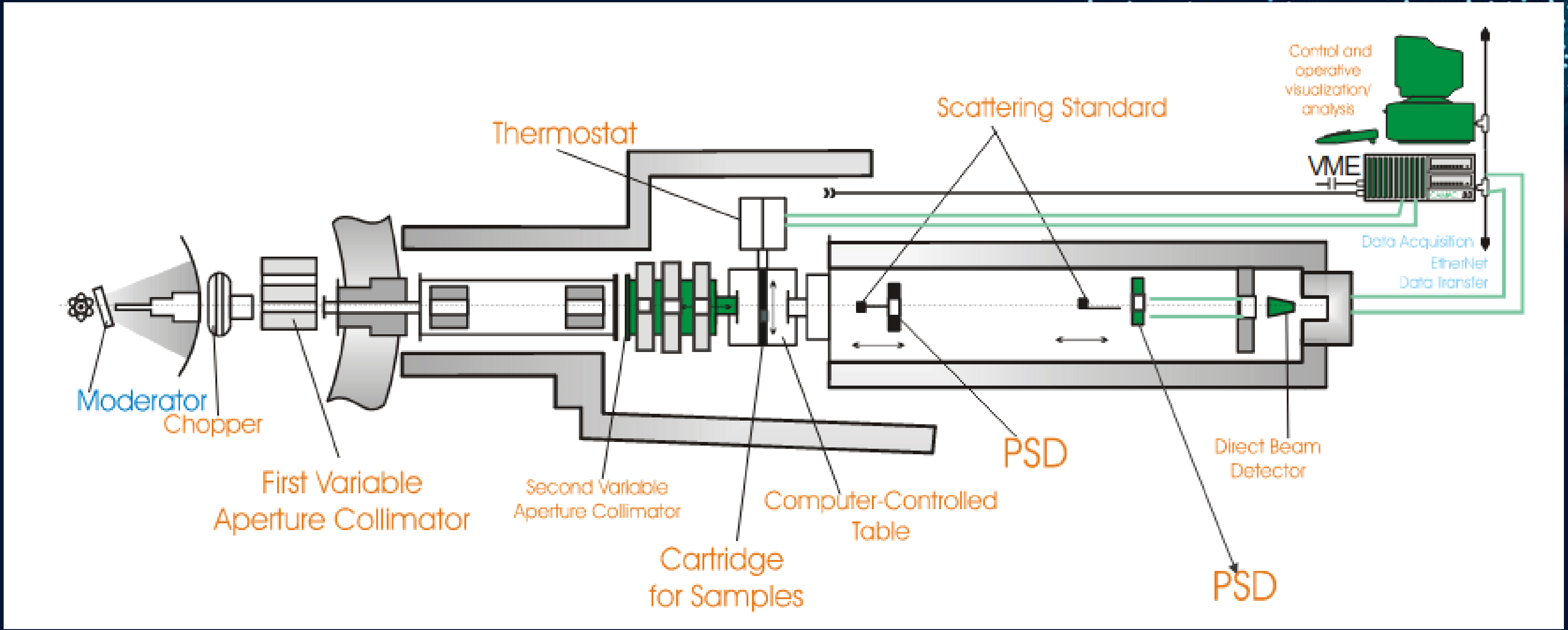


- Schematic of the SANS experiment

- Mitochondria carries out the ATP synthesis located in the inner mitochondrial membrane
- The membrane structure research was carried out
- Neutrons do not break mitochondrial activity and integrity of the inner membrane



Small-angle neutron scattering

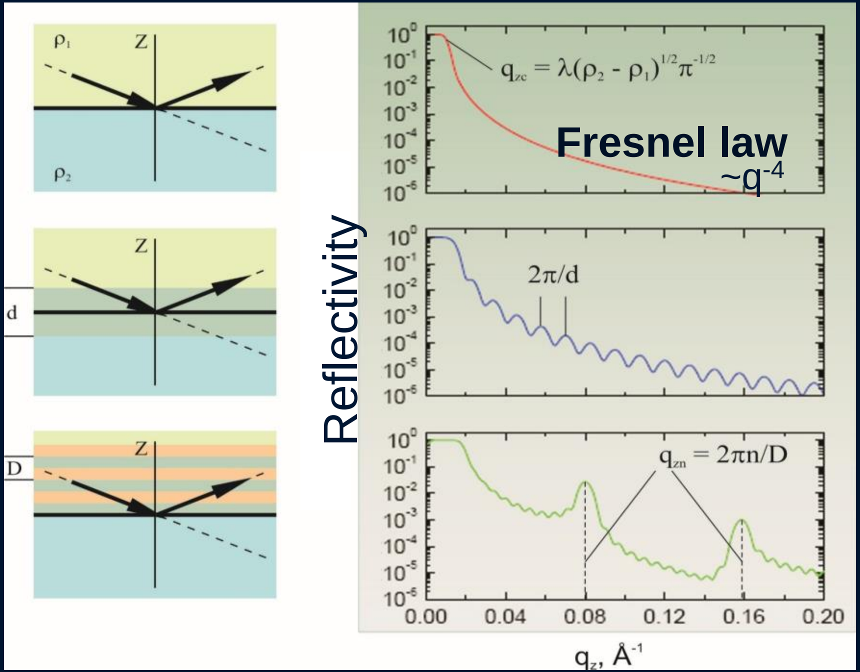


- YuMO* small-angular neutron scattering setup

*Yuri Mikhailovich Ostanevich

Neutron reflectometery

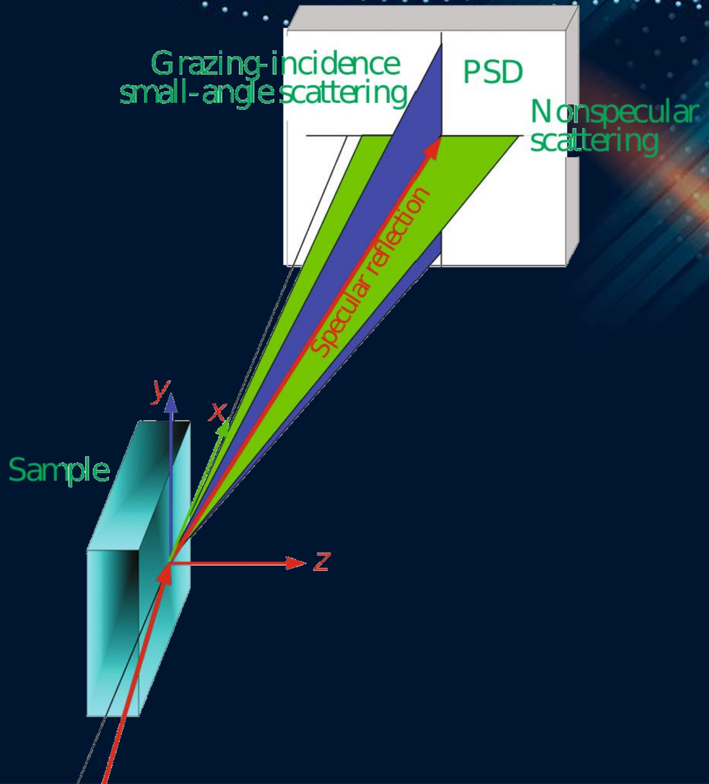
- Neutron reflectometry is a diffraction method for studying the nuclear and magnetic scattering length density



two semi-infinite mediums

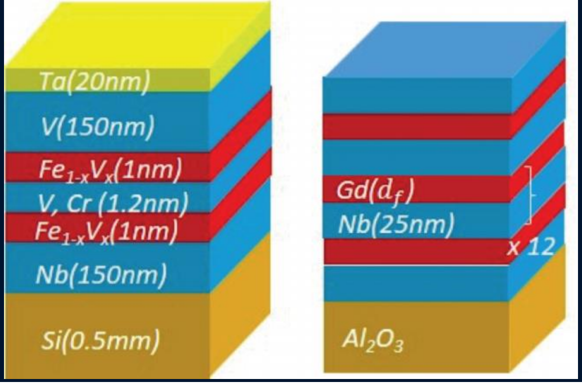
one layer

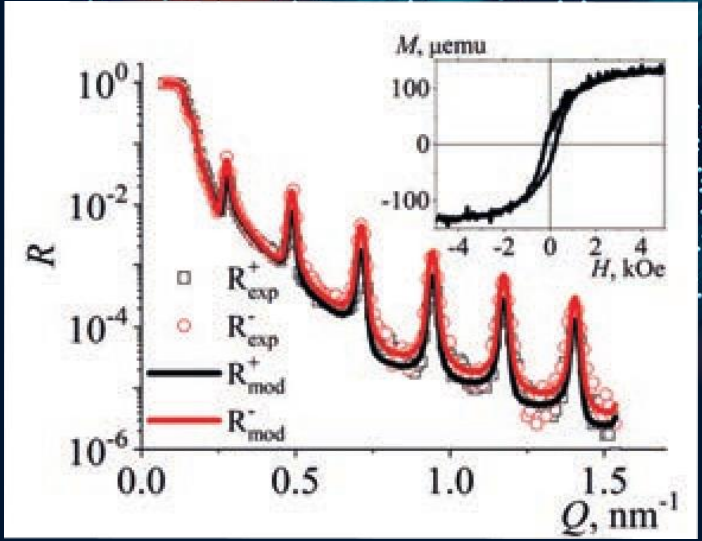
periodic multilayers

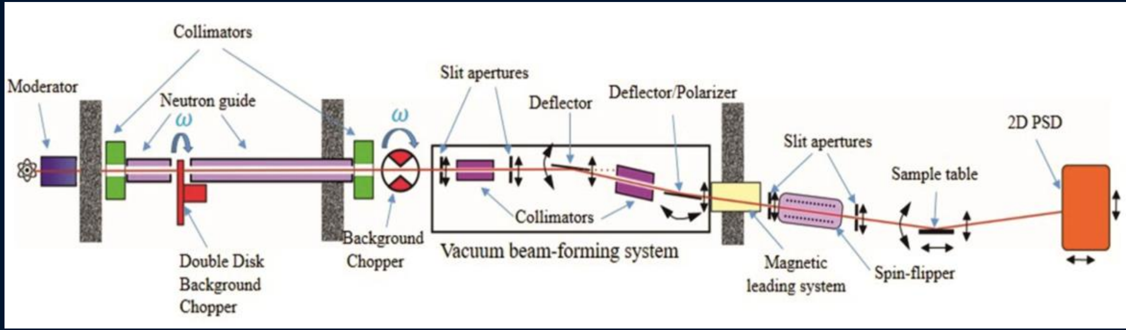


Neutron reflectometery

- Superconducting and magnetic properties of the **complex layered heterostructures** are due to superparamagnetic clusters







- **Magnetic thin films** with a layered structure open up new opportunities
- Spintronics, magnetic memory devices, quantum computing, superconducting spin valves, polarized electron injectors

Neutron inelastic scattering

- Excitations of molecules/crystals could be represented as quasiparticles: phonons. **Welcome again to the quantum world!**
- Scattering with emission of phonon is inelastic → energy transfer measurement is needed

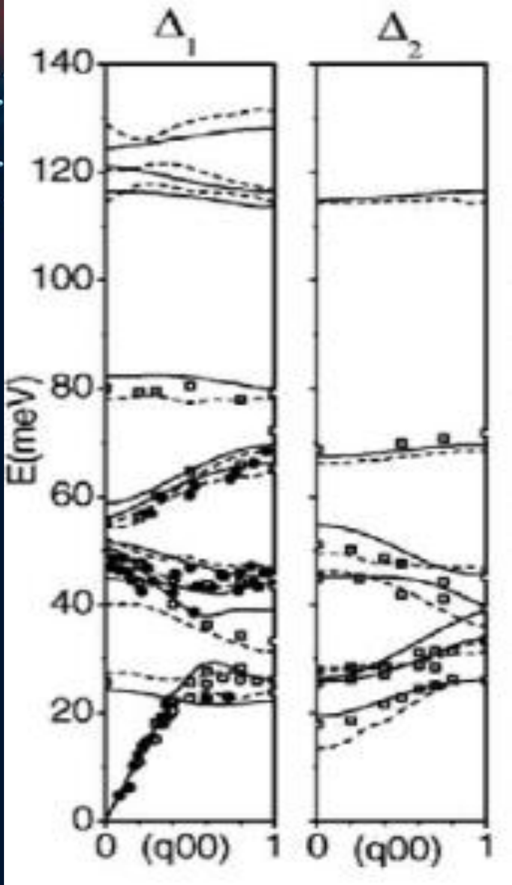
$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{\sigma}{4\pi}\frac{k_f}{k_i}NS(\vec{Q},\omega)$$

Energy transfer

Momentum transfer

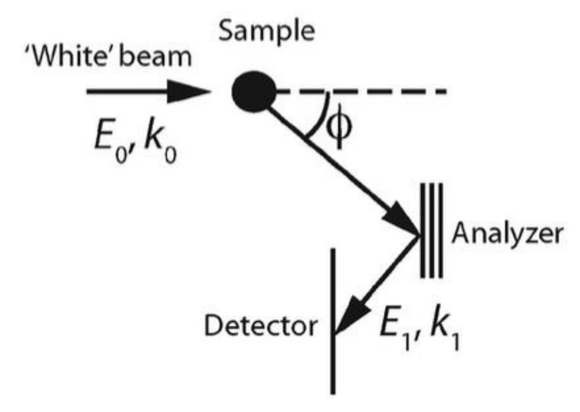
Scattering law (**information about dynamics is here!**)

- Validation of phase transition models



Phonon dispersion curves for $ZrSiO_4$

Neutron inelastic scattering
NERA



The sample is illuminated by a white incident beam, the incident energy is determined at the sample position by the measurement of the time-of-flight, and the final energy is measured by a single crystal.

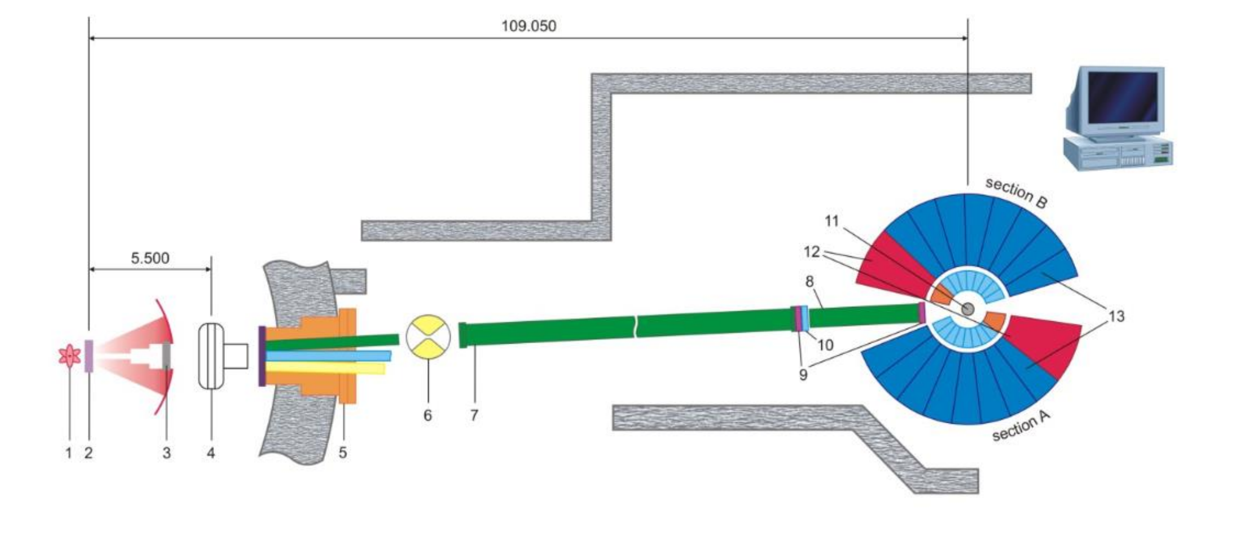


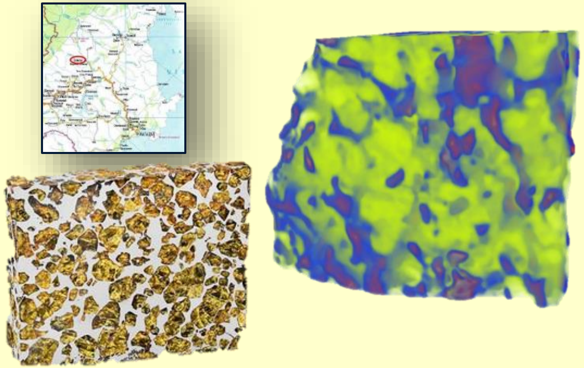
Figure 1. The layout of the NERA spectrometer: 1 – IBR-2 reactor core, 2 – thermal and cold moderators of radial horizontal channels 7-11 and tangential channels 1–9, 3 – beam shutter, 4 – fast neutron background chopper, 5 – common vacuum splitter of three Ni-mirrors neutron guides, 6 – λ-chopper of beam 7b, 7 – vacuum Ni–mirrors guide tube of neutron beam 7b, 8 – vacuum sections of beam 7b, 9 - diaphragms of incident beam, 10 –monitor, 11 – sample position, 12 – NPD sections, 13 – INS and QENS sections.

Neutron tomography

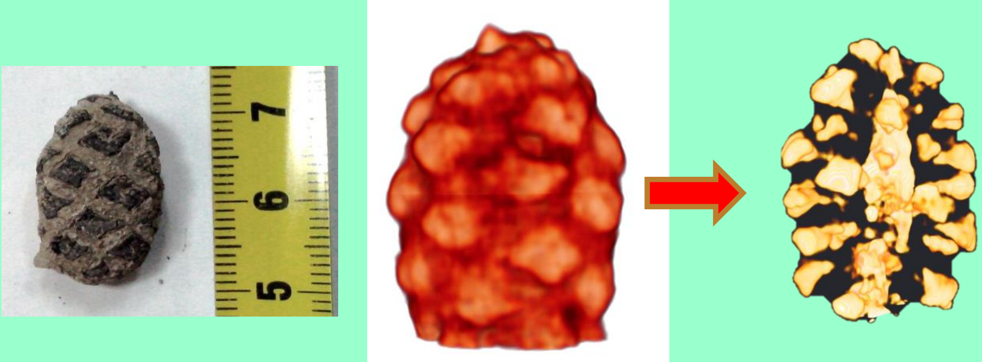
Radiography
(see more in V. Smirnova report)



Tomography



3D reconstruction of Fe-Ni alloy distribution in Seimchan meteorite



3D reconstruction of internal structure of Protosequoia cone (cretaceous period) from Paleontological Institute RAS

Conclusion

- Neutrons have been discovered about 90 years ago, but there are anyway several non-solved puzzles
- Neutron is a unique tool for studying matter on different levels of organization: from fundamental nuclear forces to nanoparticles
- Neutron physics is interesting and attractive area of research :)

THANKS!

Questions?