Nuclear Physics Investigations at FLNP

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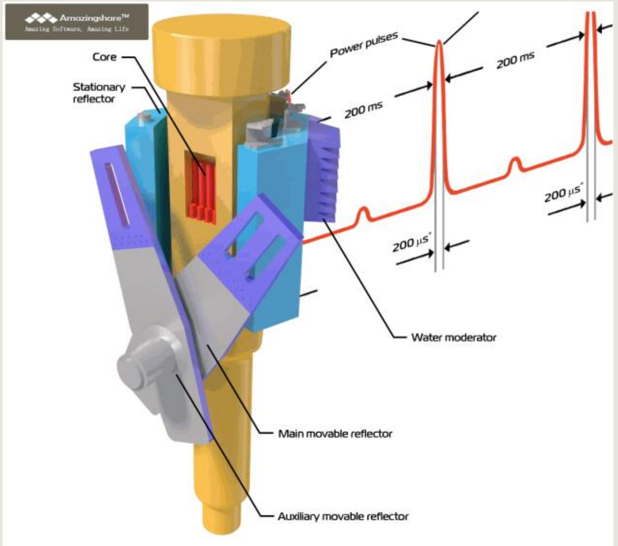
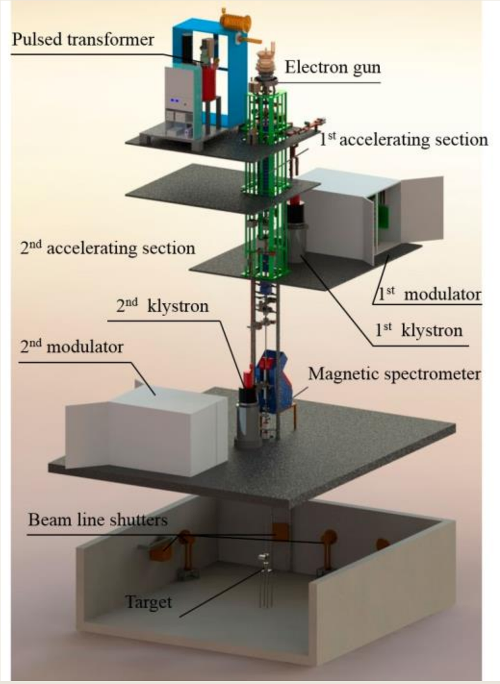
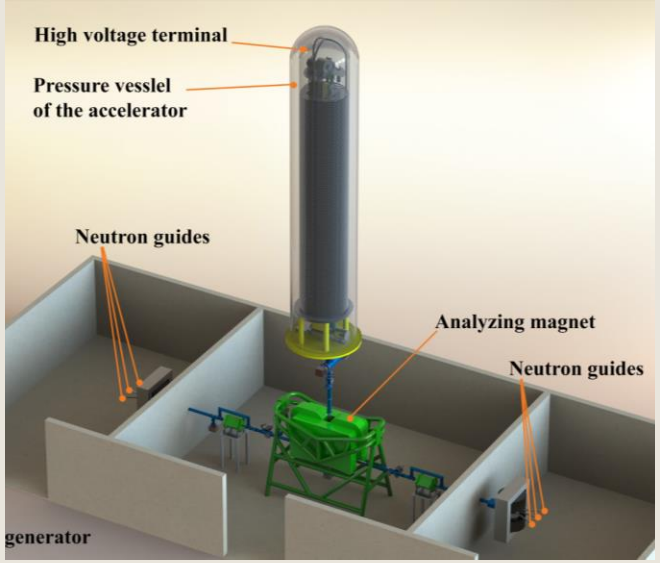
Neutron sources at FLNP



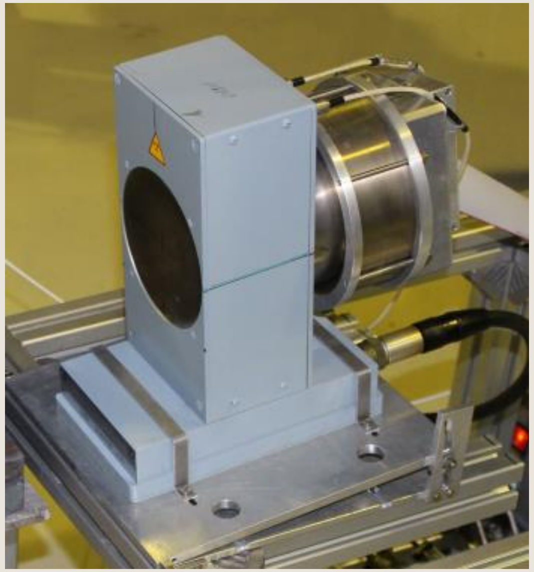
IBR-2: thermal neutrons, lowest resonances



IREN: resonance neutrons



EG-5: fast neutrons up to 4 MeV



Neutron generator: fast neutrons 14.1 MeV

Nuclear physics: areas of research

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

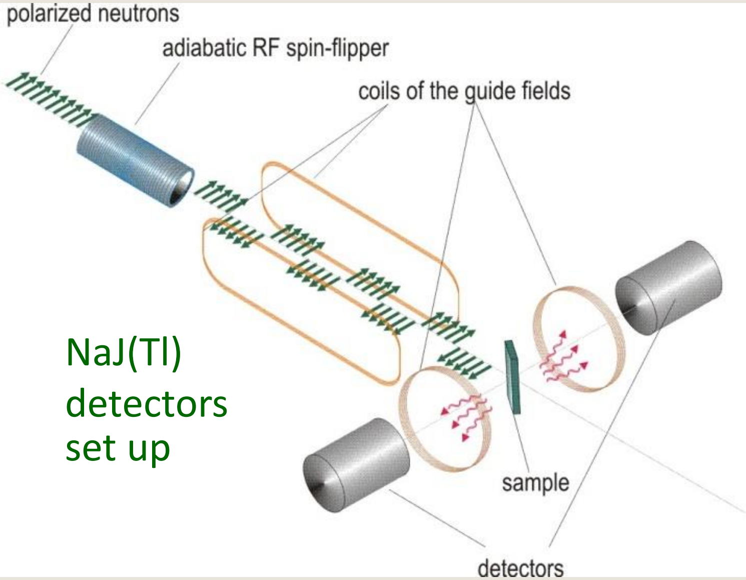
Search for the weak neutral current in the nucleon-nucleon interaction: P-odd effects

Determination of the fπ weak neutral current coupling constant from the experimental P-odd correlations

Experiments are performed at ILL (Grenoble)

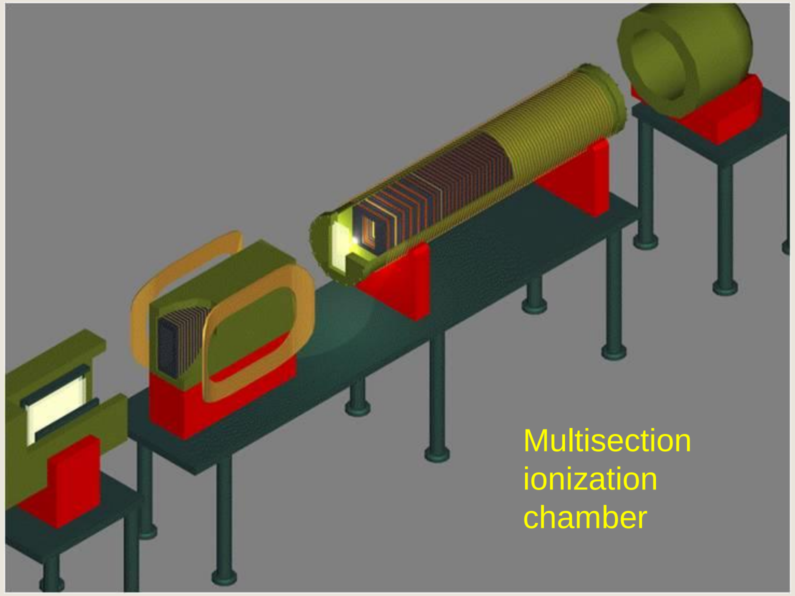
10B(n,α)7Li* → 7Li + γ (Eγ = 0.478 MeV)
γ-ray asymmetry

expected value $\alpha_\gamma = 5.2 \cdot 10^{-8}$ (DDH)



6Li(n,α)3H triton-asymmetry
$^{10}B(n,\alpha)^{7}Li$ α-asymmetry

expected value $\alpha_t = -\,2.7 \cdot 10^{-7}$ (DDH)

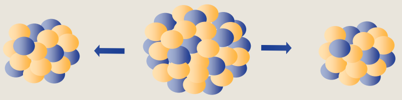


For the first time in the world, the P-odd coefficients were measured with a sensitivity of ~10-8 asymmetries in reactions of cold neutrons with light nuclei:

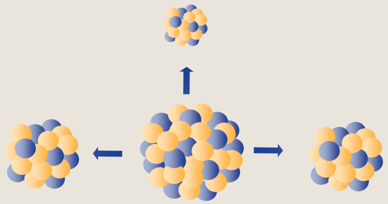
$\alpha(^{6}Li, t) = -(8{,}8 \pm 2{,}1) \cdot 10^{-8}$; $\alpha(^{10}B, \alpha) = -(11{,}2 \pm 3{,}4) \cdot 10^{-8}$; $\alpha(^{10}B, \gamma) = (0{,}0 \pm 2{,}6) \cdot 10^{-8}$

Studies of nuclear fission

Binary Fission



Ternary Fission

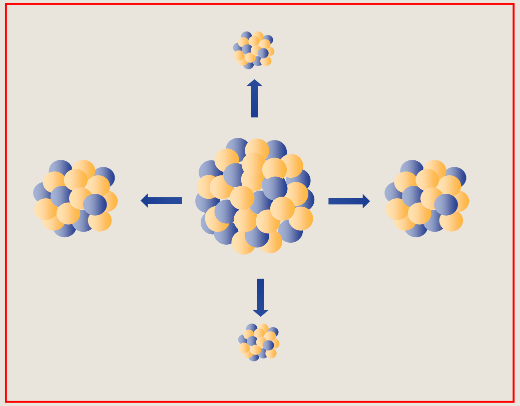


The two heavy fragments are sometimes accompanied by a Light Charged Particle (LCP): Ternary fission

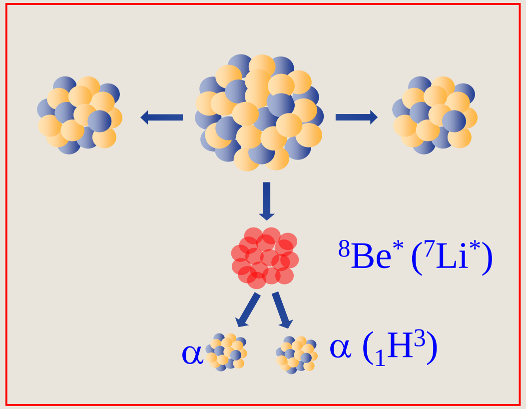
The possibility of fission into three charged nuclei has been pointed out by theoretical physicists, predicting a liberation of maximum energy of 210-220 MeV, even 10-20 MeV higher than that of binary fission.

- N.Bohr and J.A.Wheeler, Phys.Rev.50, 426 (1939)
- R.D.,Present, Phys.Rev.59, 466 (1941)

"True" Quaternary Fission

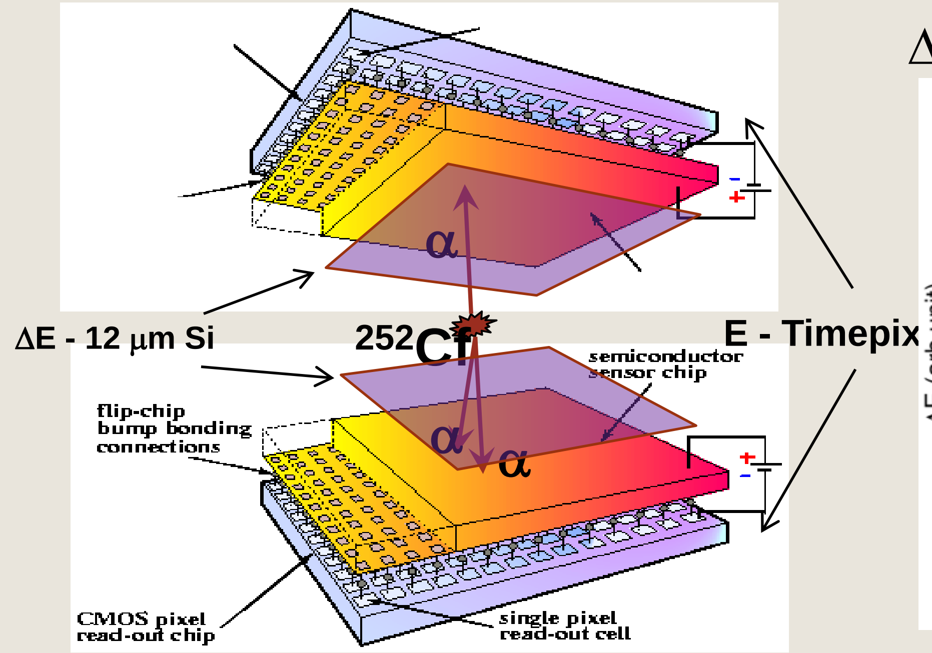


"Pseudo" Quaternary Fission

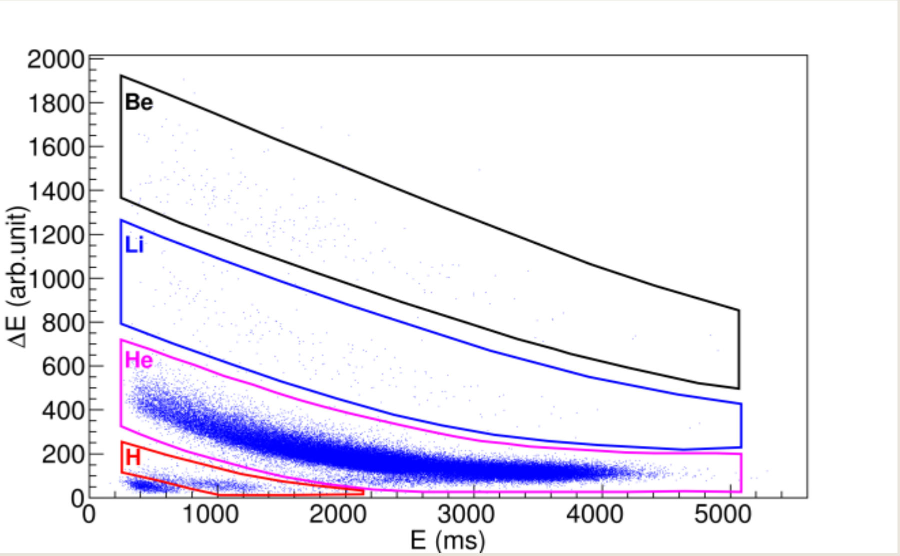


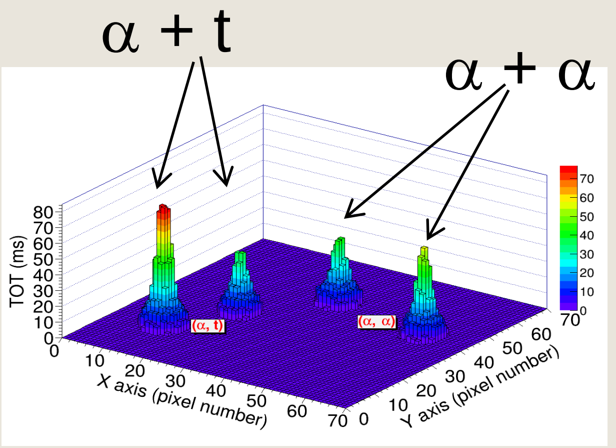
Tsien San-Tsiang, Phys. Rev. 71 (1947), 382

Measurement of ternary and quaternary fission of ^{252}Cf



ΔE-E method of particle identification



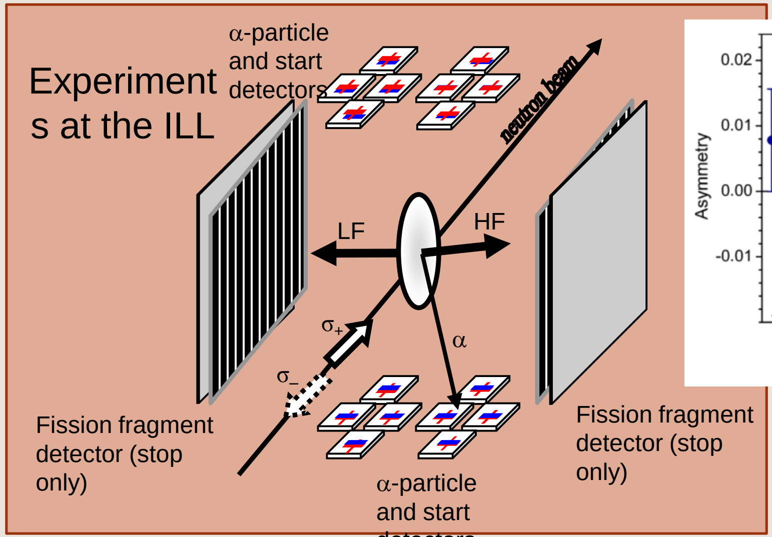


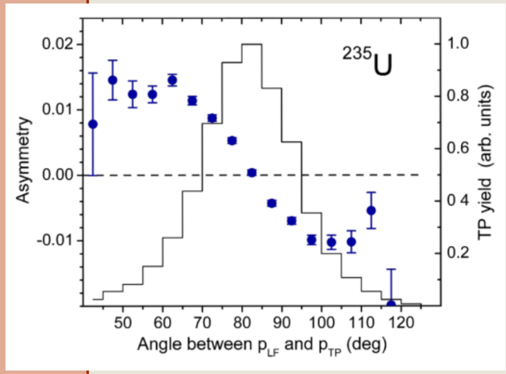
Measured parameters of rare fission modes:

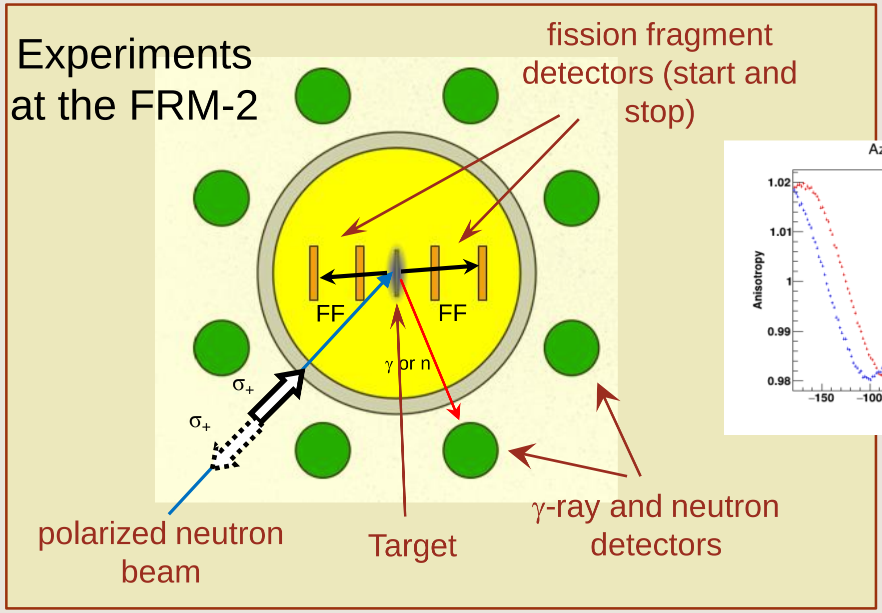
Particle	Energy (MeV)	σ (MeV)	Yield (per 10^4 α)	Energy (MeV) (Ref.)	Yield (per 10^4 α) (Ref.)
Be (α, α) (g.s.*)	22.76(90)	5.942(433)	5.34(32)	10 (per α)[1]	10(6)[1]
Be (α, α) (1st ex. s.*)	23.46(25)	5.326(214)	0.62(1)	11.2(8) (per α)[1]	2(1)[1]
Li (α, t) (2nd ex. s.*)	19.25(34)	4.279(430)	0.13(1)	-	0.3(1)[1]
(α, α)	14.32(96)	4.919(370)	1.12(8)	13.7(8)[1]	3(1)[1]
(α, t)	13.77(25) 8.51(1.8)	4.397(855) 3.356(708)	0.31(5)	-	0.4(1)[1]

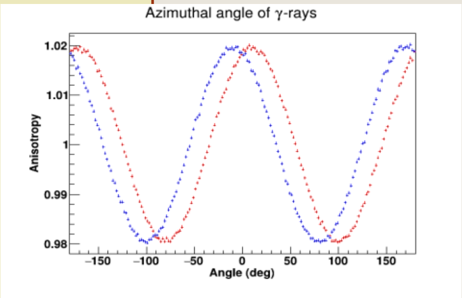
Measurements of T-odd effects in the polarized neutron induced fission

Experiments are performed at the ILL reactor in Grenoble and FRM-2 reactor in Munich in large international collaborations









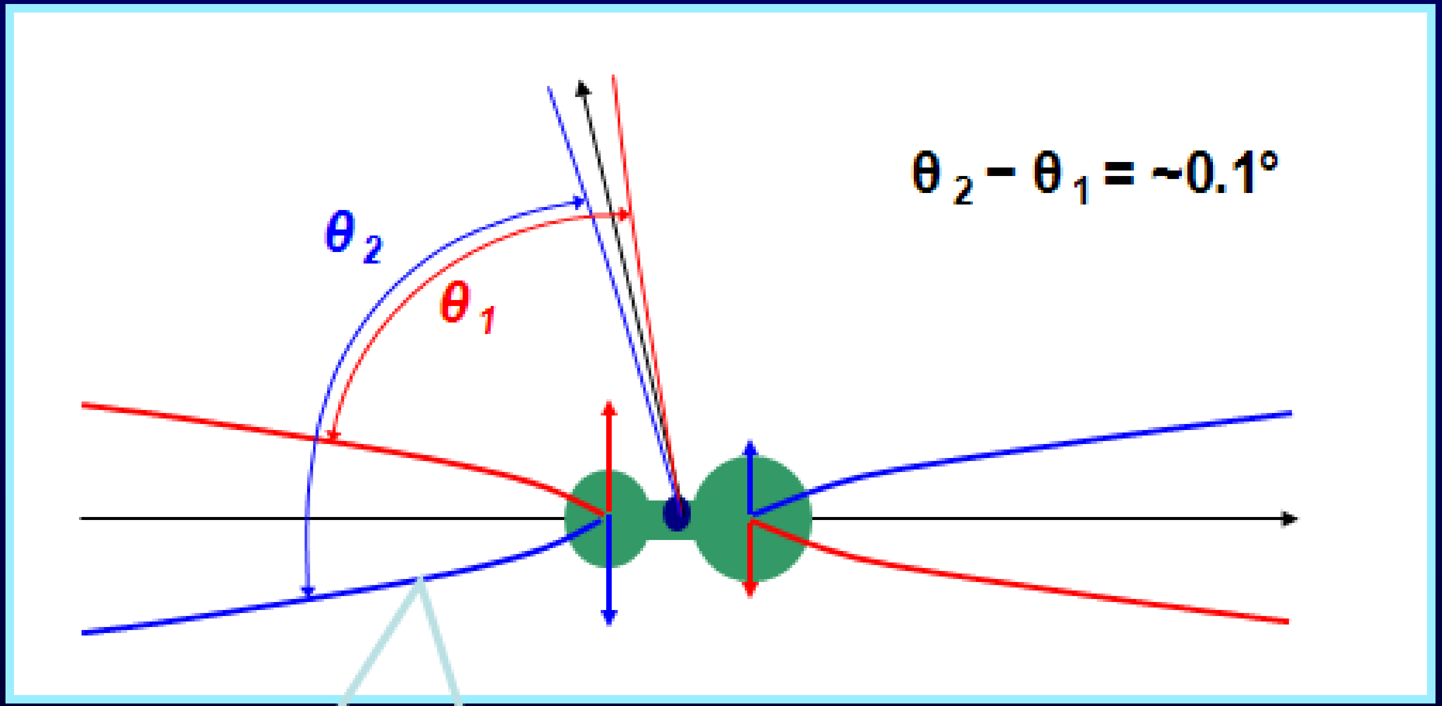
ROT- and TRI-effects for the α-particle emission

nuclei	spin	ROT (degree of rotation)	TRI (x 10^{-3})
^{233}U	2+, 3+	0.03(1)	-3.9(1)
^{235}U	3-, 4-	0.215(5)	1.7(2)
^{239}Pu	0^+, 1^+	0.020(3)	-0.23(9)

ROT-effect for the γ-ray and neutron emission

nuclei	Angle to the fission axis	γ-rays (x10^{-5})	Neutrons (x10^{-5})
^{233}U	22.5	+2.8±1.7	+4.8±1.6
^{235}U	22.5	-12.9±2.4	-21.2±2.5

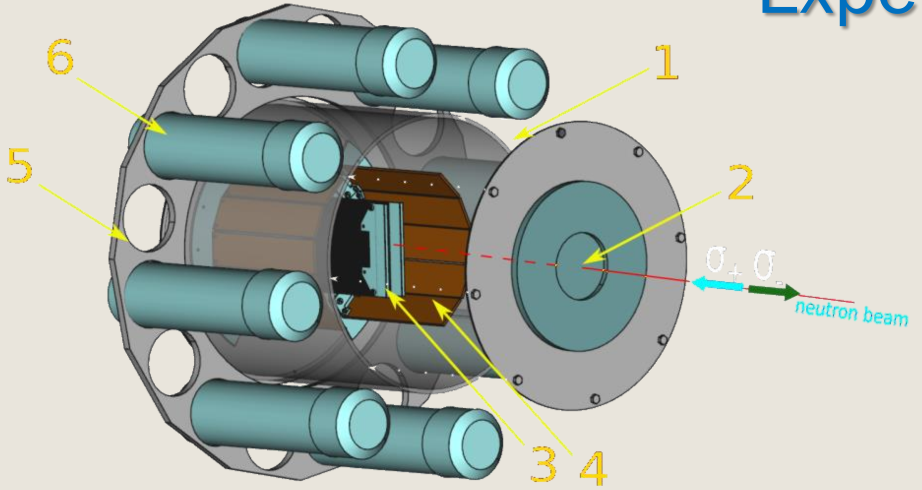
Model of the ROT-effect



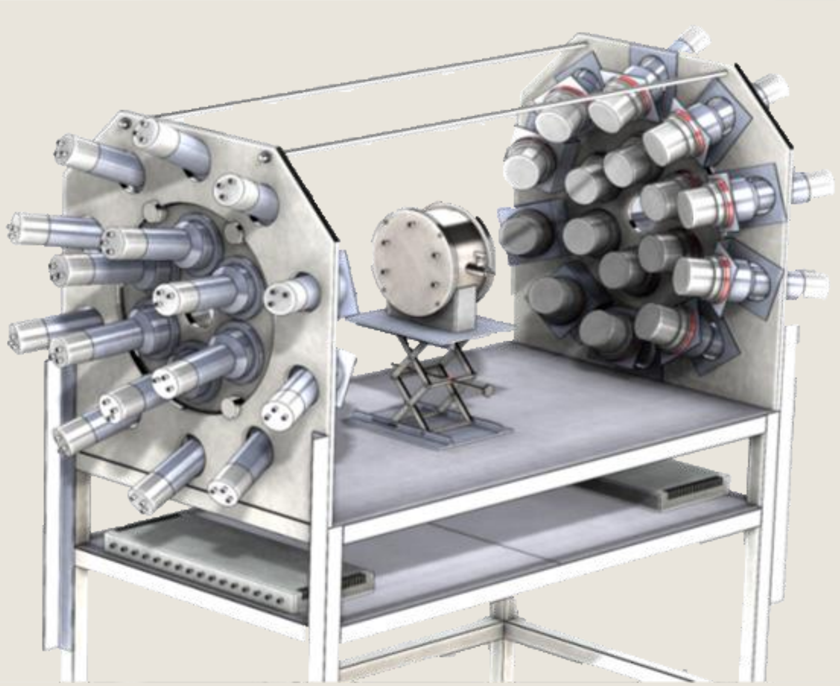
Trajectories of fission products for two directions of the scissioning nucleus rotation (schematically)

Nuclear fission studies

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

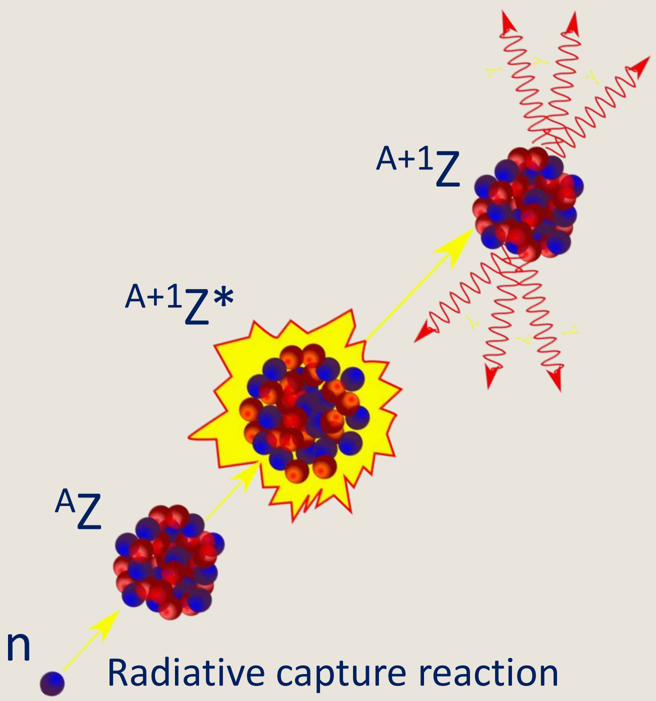


- Experimental setup for ROT-effect study
- 1 — fission chamber, 2 — Al input chamber window, 3, 4 — fission fragment detectors based on position-sensitive multiwire proportional counters (start and stop detectors), 5 — holder, 6 — scintillation plastic detectors of γ-quanta and neutrons
- Angular distributions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

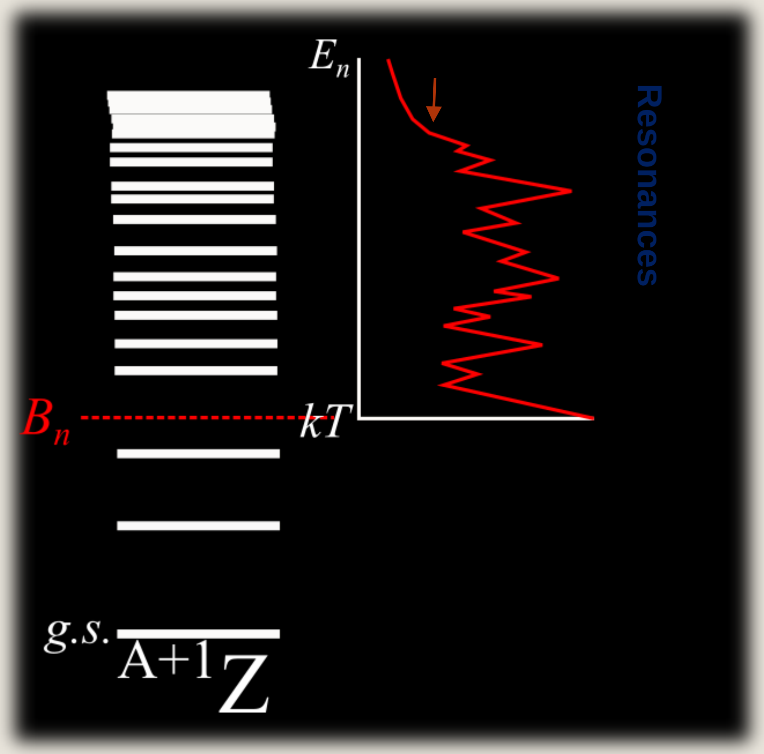
Neutron resonances

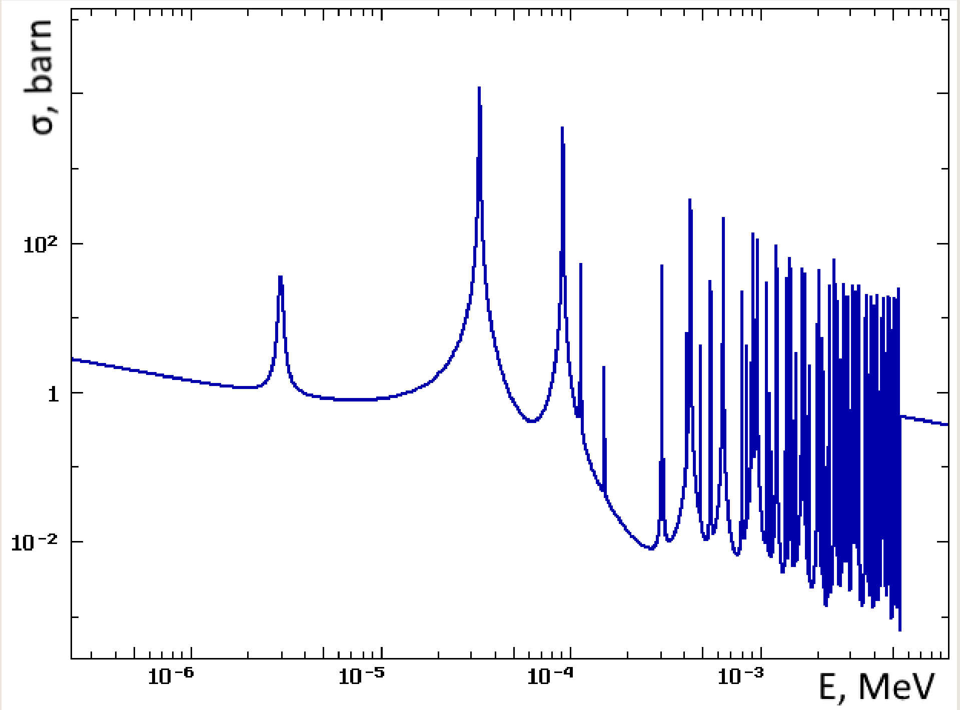
- Nucleus is a quantum system → energy levels

- 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

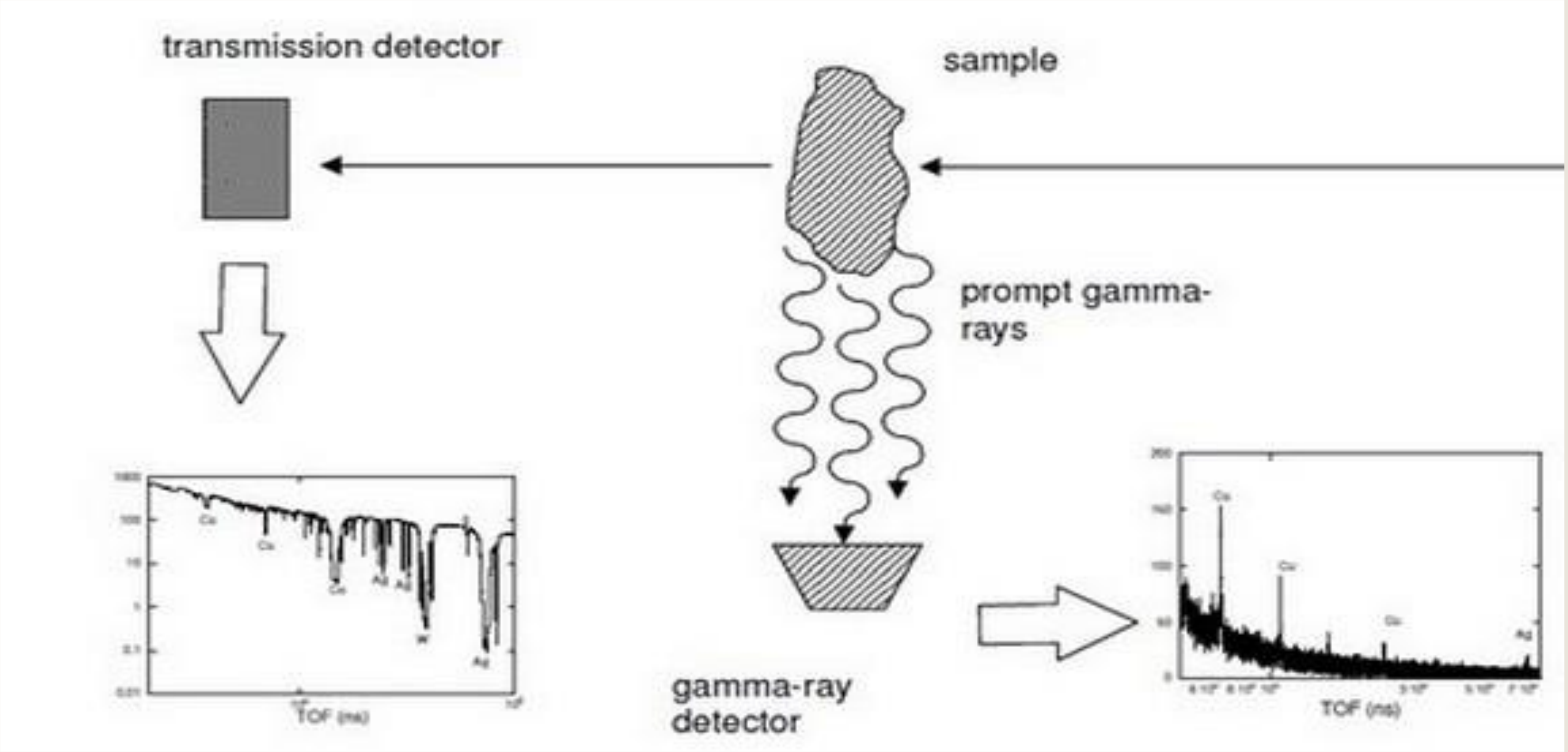


Radiative capture reaction

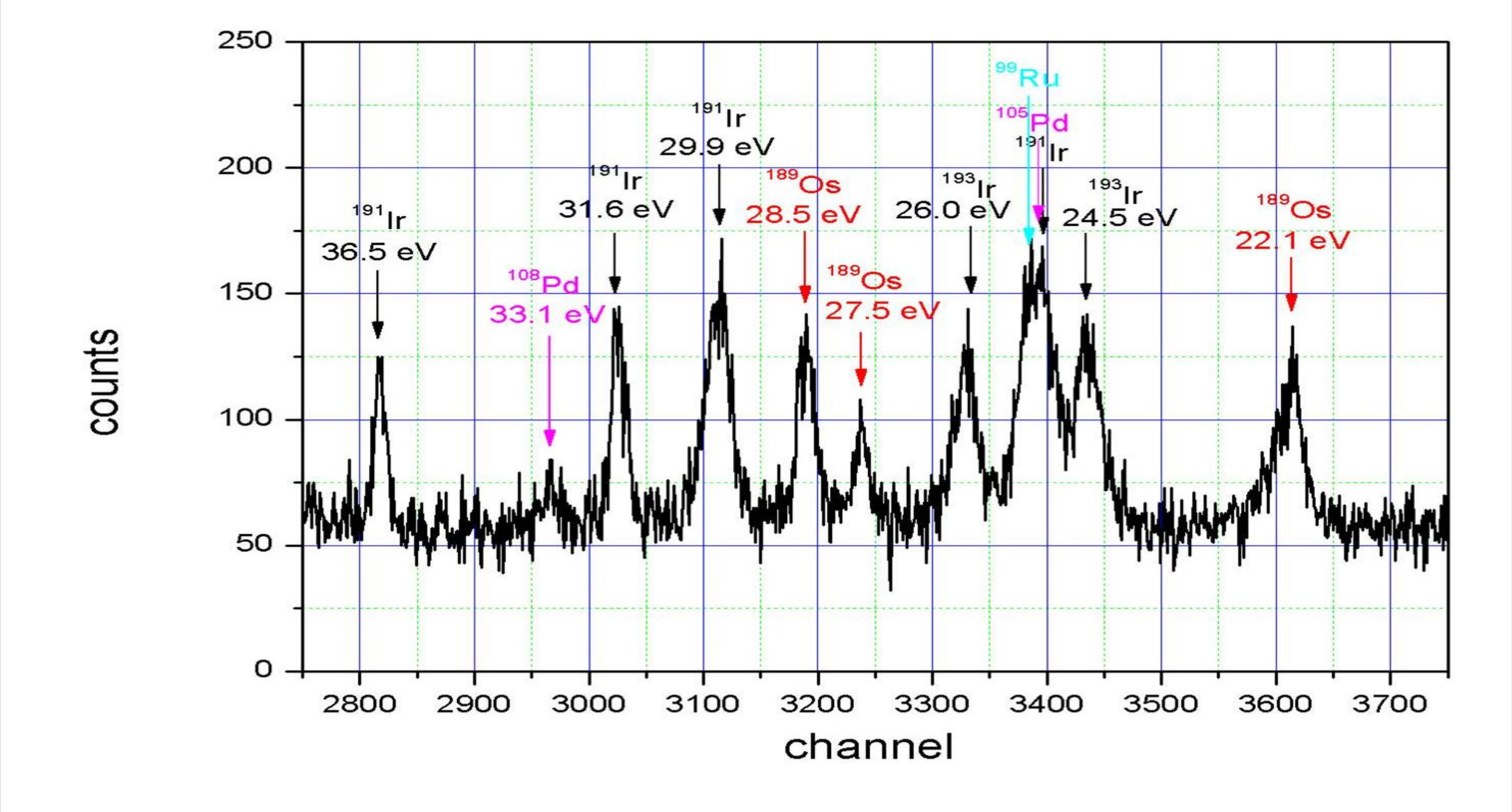




Neutrons capture vs neutron transmission



Experiments at IREN: Non-destructive analysis of the geological samples



Element	Mass of the element in the sample (g)
Pt	2.7±0.3
Pd	0.1±0.02
Ir	5.2±0.6
Ru	1.14±0.2
Os	4.3±0.5

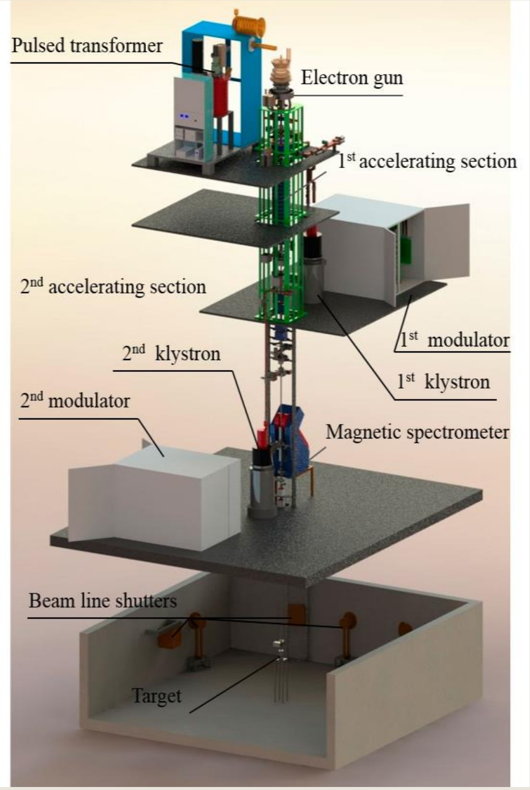
Advantages

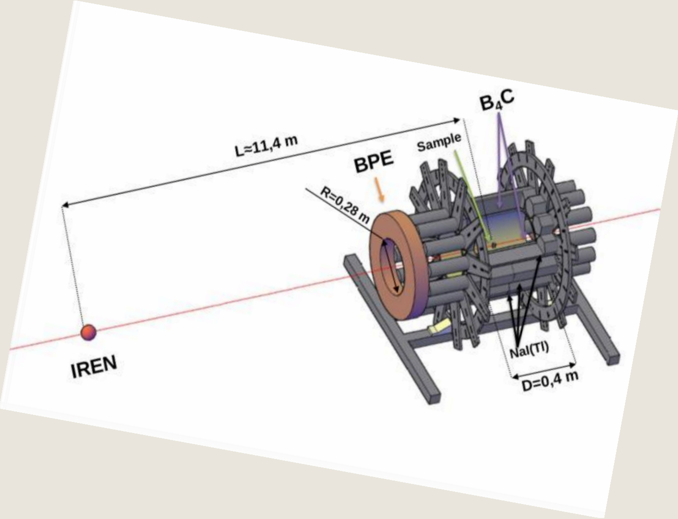
- fully nondestructive
- bulk investigation
- negligible residual activity
- sensitivity to the isotopic composition
- possibility to investigate radioactive samples

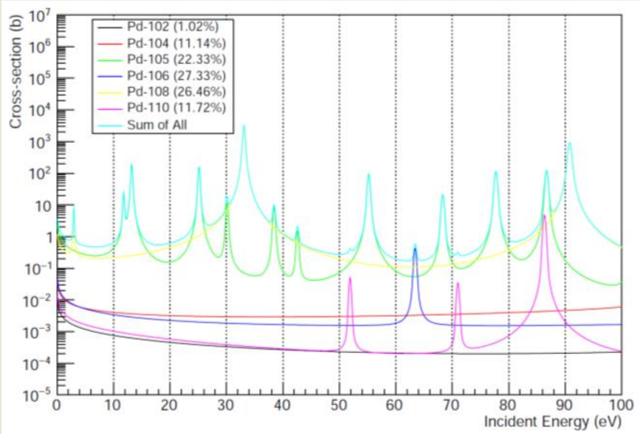
The use of resonance neutron method for investigating parts of the “Proton” rocket engine

One hypothesis for crash of the Proton rocket is presence of palladium in some critical components of the engine

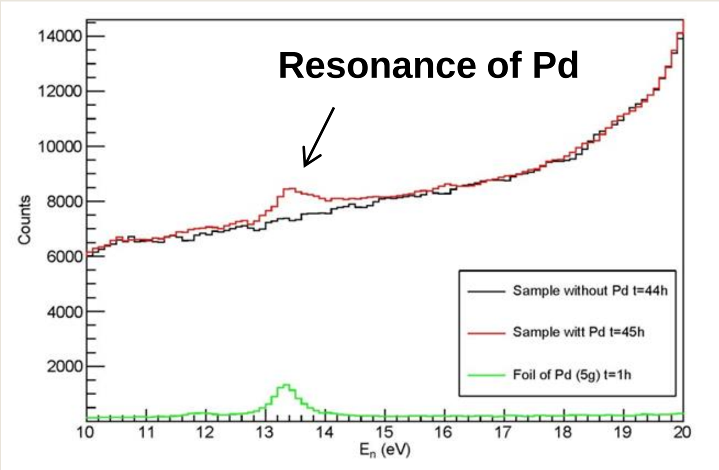
The use of resonance neutron method for investigating parts of the “Proton” rocket engine







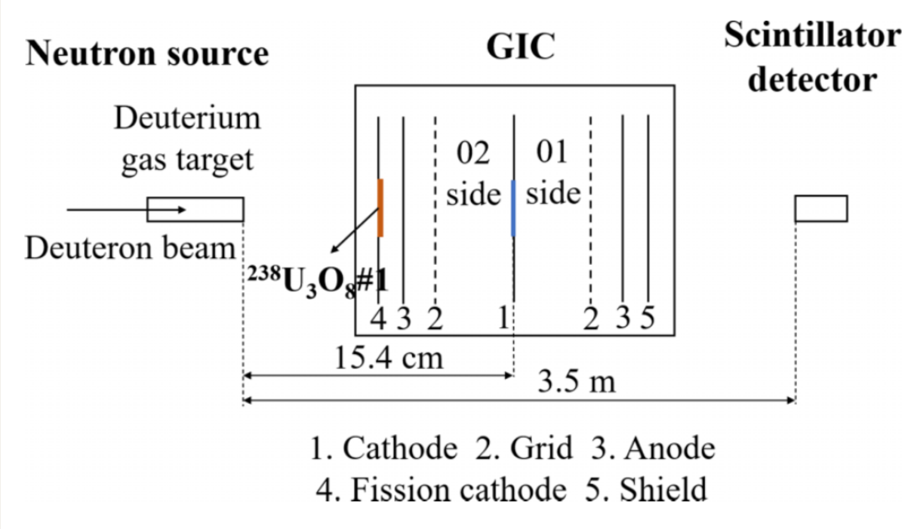
Neutron resonances

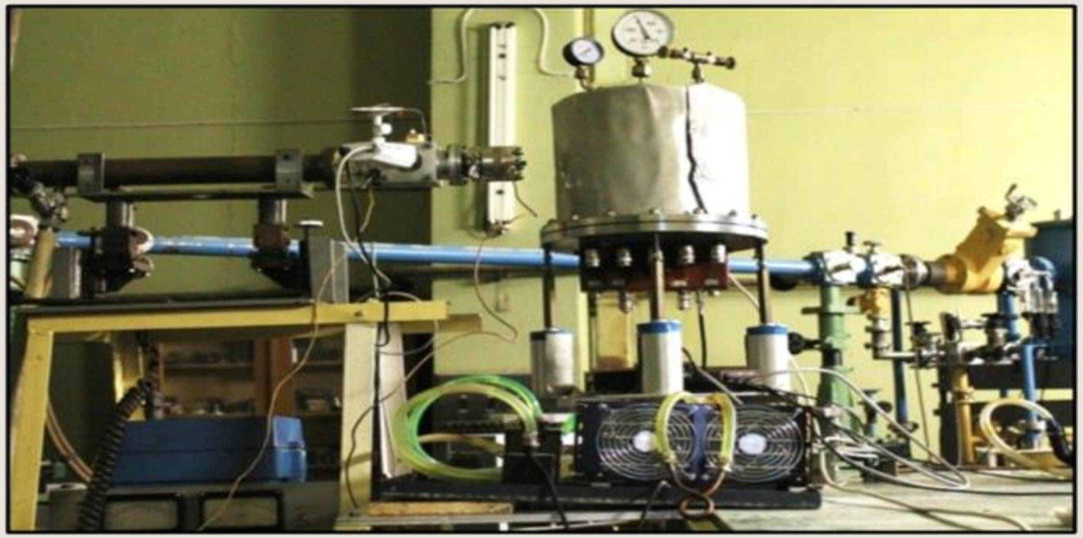


The amount of Pd in the ~60 g sample was found to be 98 ± 10 mg.
Estimated sensitivity of the method: ~1.5 × 10^{-3} g/g

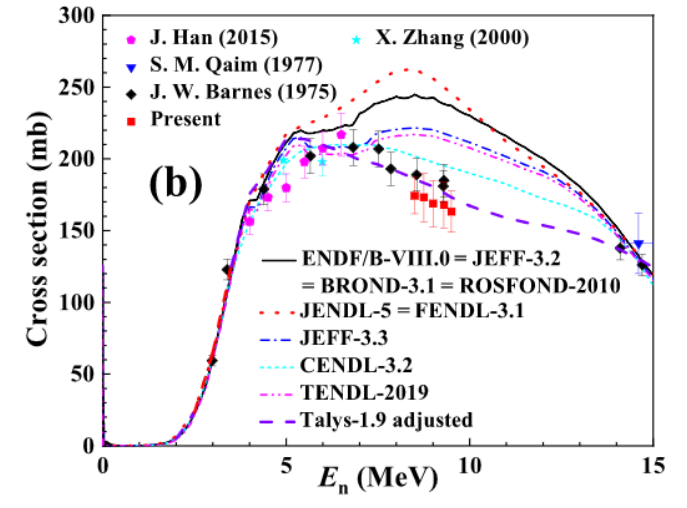
Measurements on (n,p), (n,α) reaction cross sections

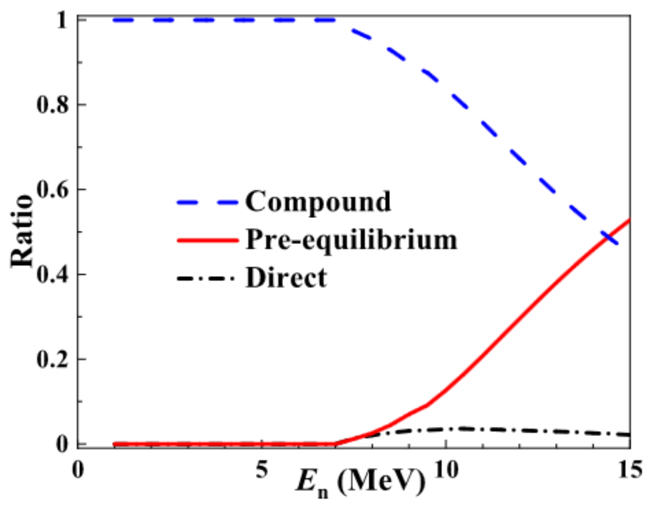
Experiments at EG-5 (FLNP), EG-4.5 (Peking University, Beijing) and HI-13 (Chinese Institute of Atomic Energy, Beijing)





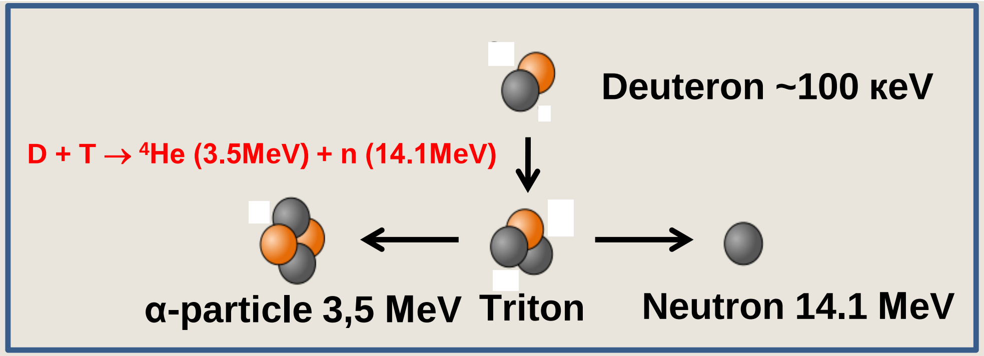
- Experimental setup for (*n*,*α*) investigation
- ion. chamber is used to measure energies of *α*
- 238U for neutron fluence monitoring, n-detector for measurement of n-energy
- Estimation of nuclear reaction mechanisms impacts in result



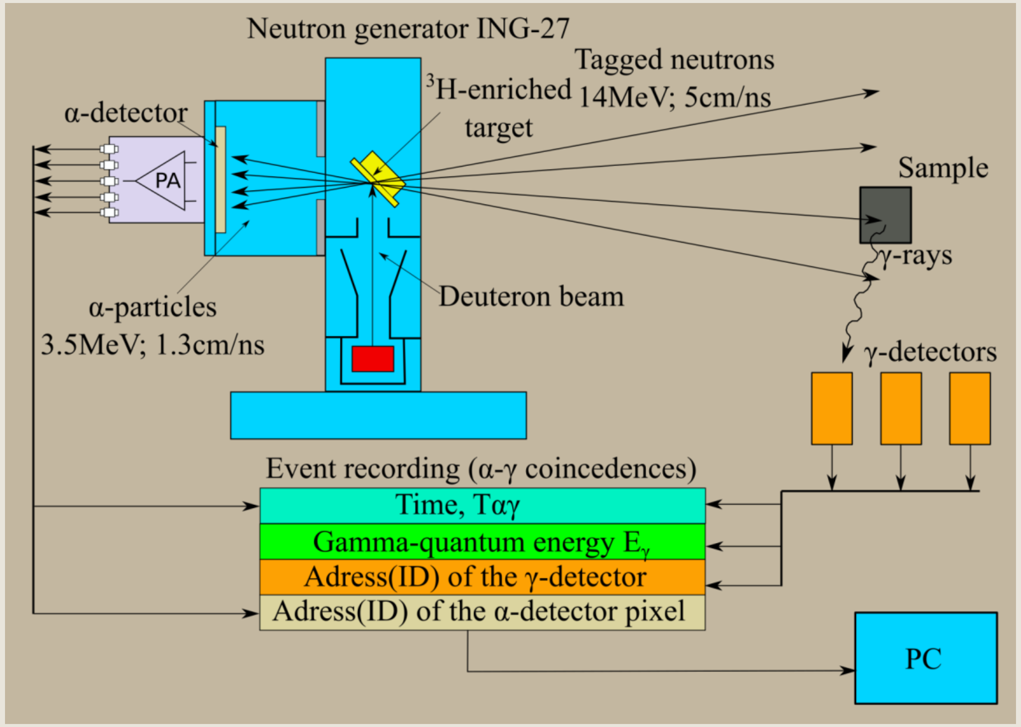


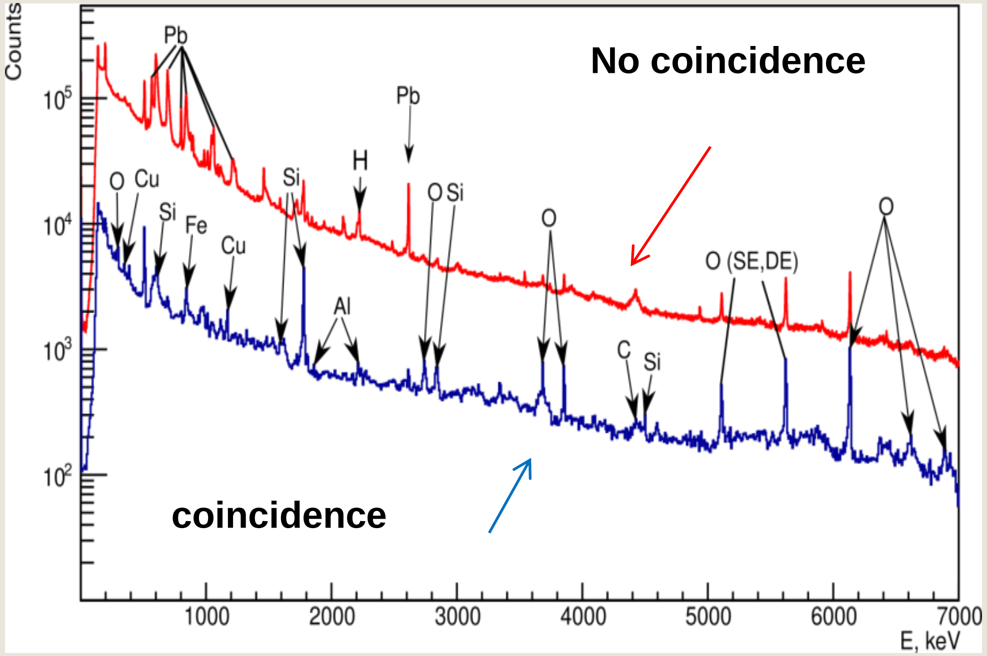
Project TANGRA: TAgged Neutrons & Gamma RAys

Tagged Neutron Method



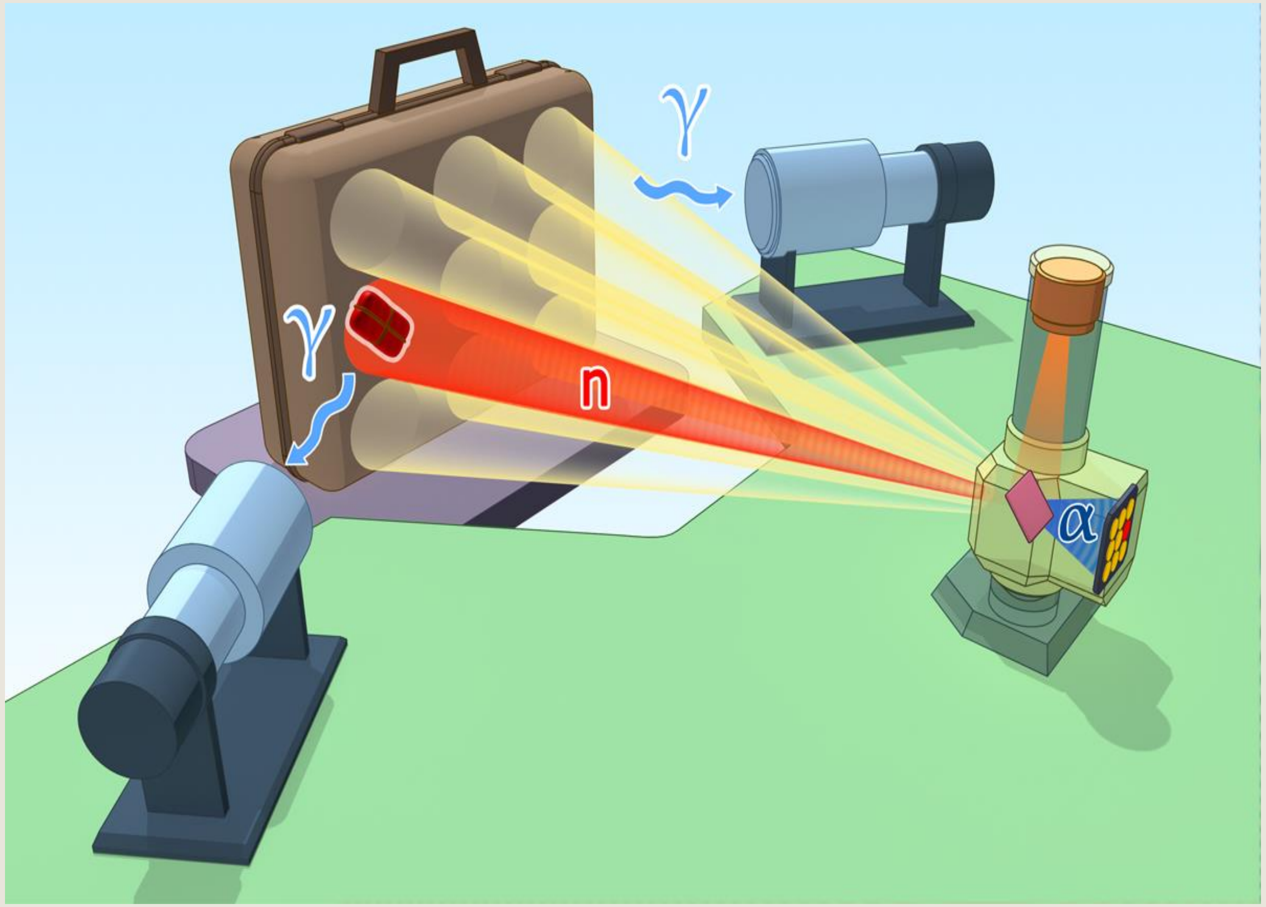
Neutron generator ING-27 with built-in position sensitive α-detector

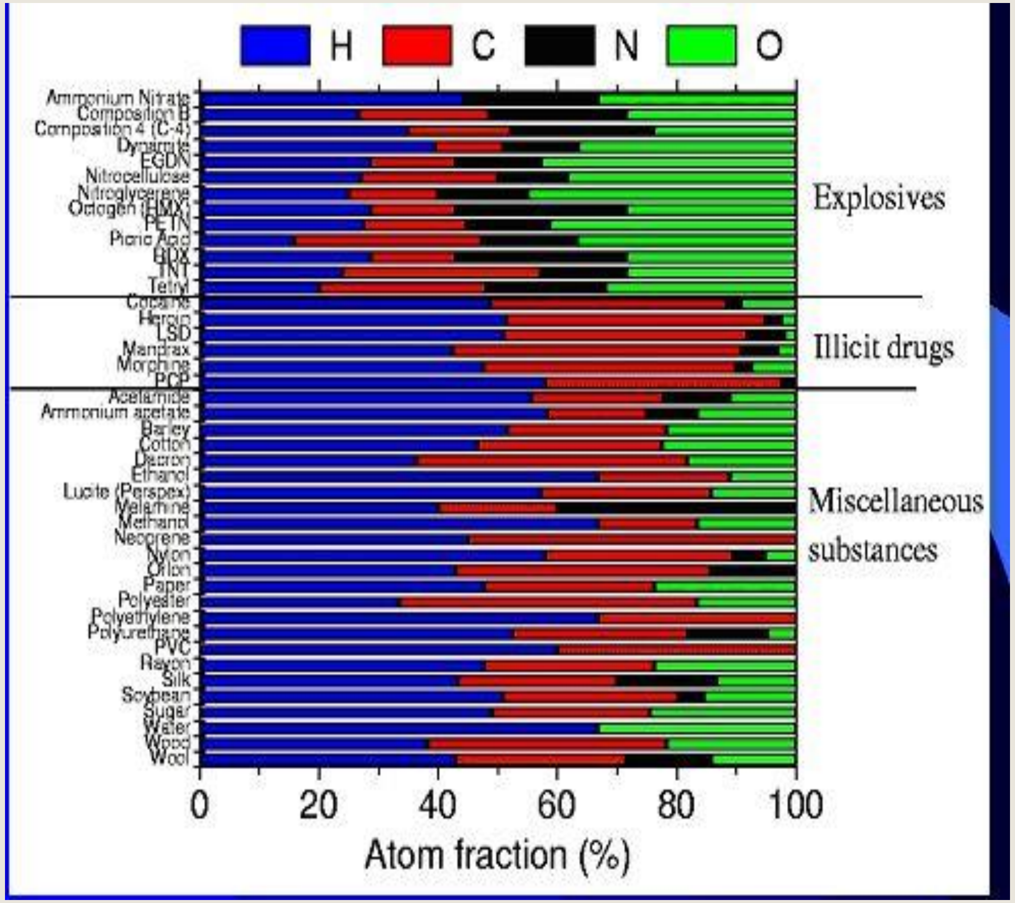




Elements can be identified by their characteristic spectra.

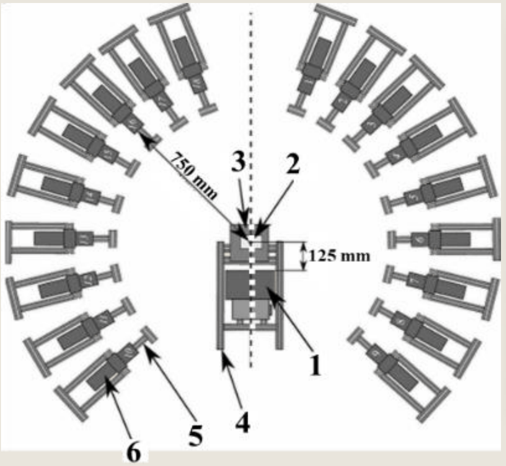
Using tagged neutron method for detecting illegal and hazardous substances



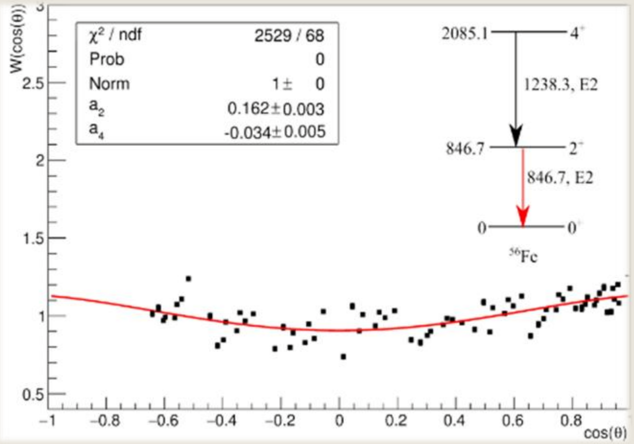


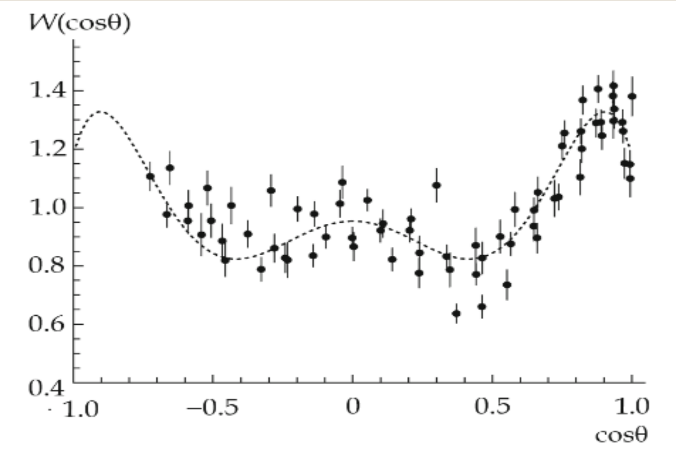
TANGRA PROJECT

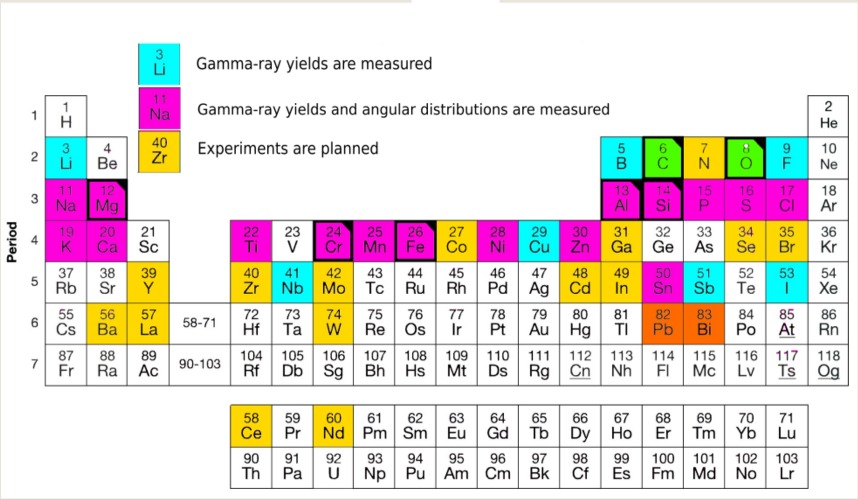
A configuration of the set-up consisting of 18 BGO detectors has been created.



Gamma-spectra and angular distributions of gamma ray have been measured in inelastic neutron scattering reactions for 20 nuclei.



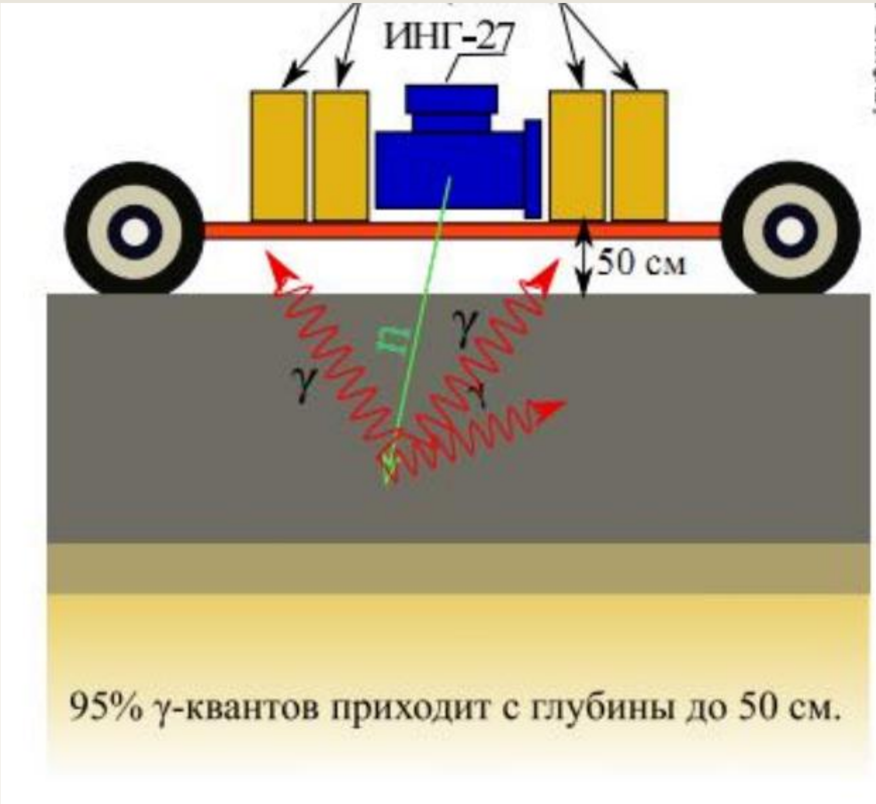




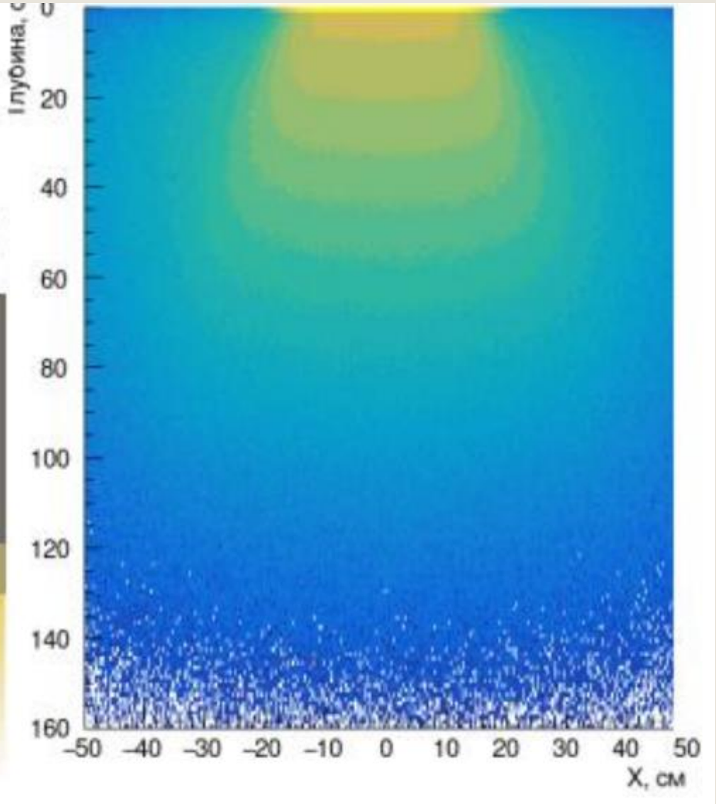
Examples of measured angular distributions for 847 keV gamma transition in iron and 6.13 MeV transitions in oxygen.

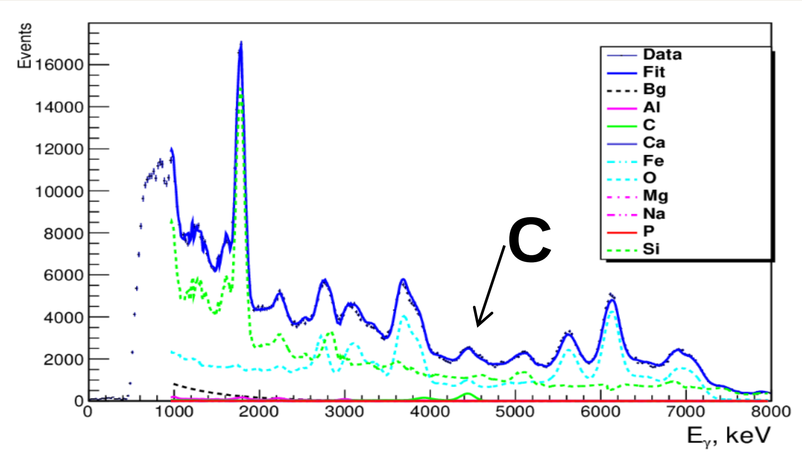
Determination of carbon in soil using tagged neutron method

BGO detectors



distribution of reactions by depth

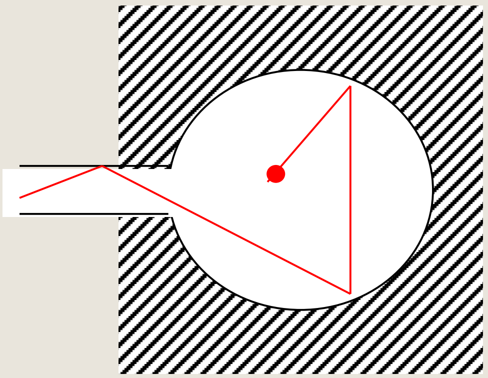


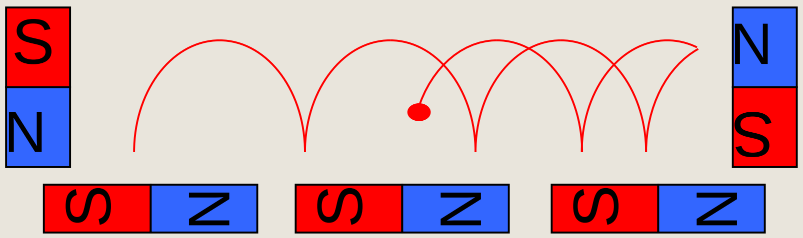


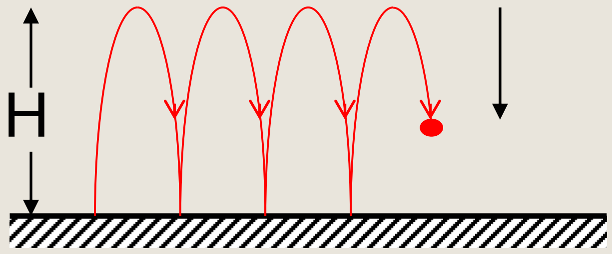
Carbon concentration is determined by the amplitude of the characteristic 4.44 MeV gamma-line.

Ultracold neutrons (UCN)

Potential of interaction of slow neutrons with matter :

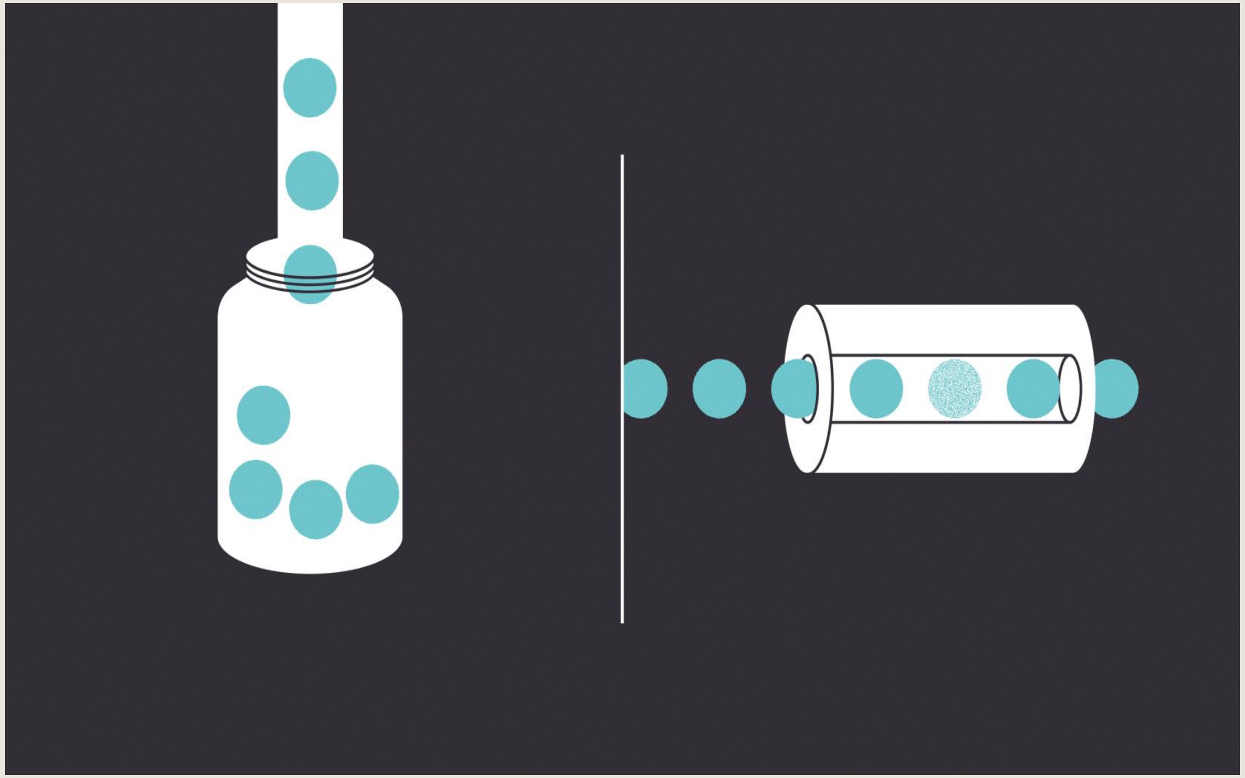


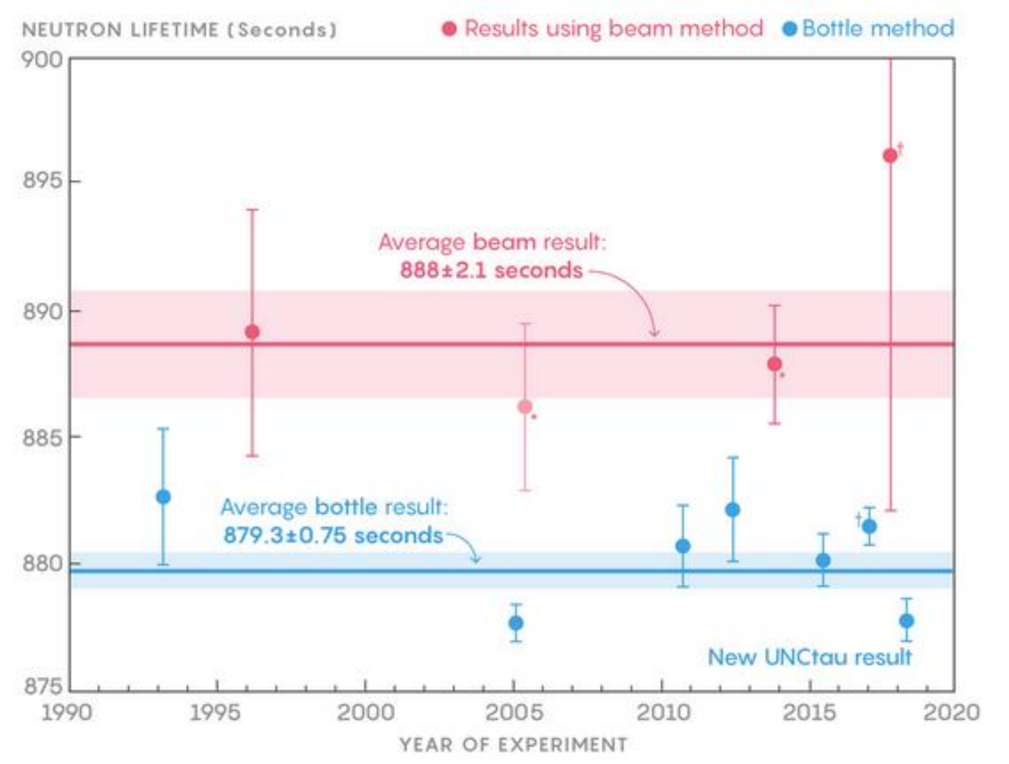




Effective potential	~ 10^{-7} **eV**
Gravity:	~ 10^{-7} **eV** / Meter
Magnetic field:	~ 10^{-7} **eV** / Tesla

Measurements of the neutron lifetime τ_n



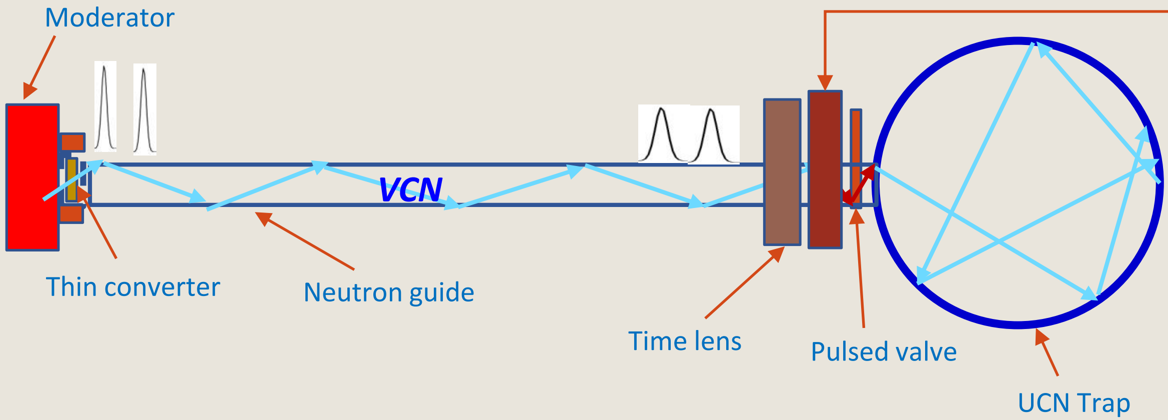


Storage experiments with UCN Beam experiments with cold neutrons

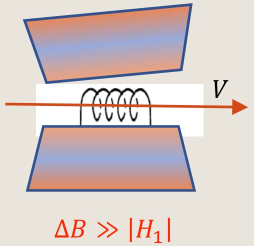
Neutron Lifetime Puzzle

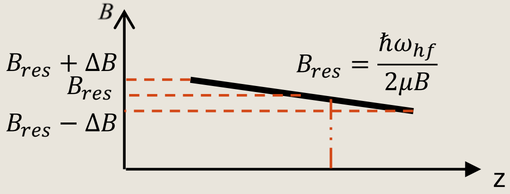
Conception of a UCN source @ periodic pulsed reactor with pulsed accumulation of UCN in a trap

If to decelerate VCN to UCN by local device which is placed near the trap → The flux of neutrons, which can be trapped after deceleration, will have a pulsed structure



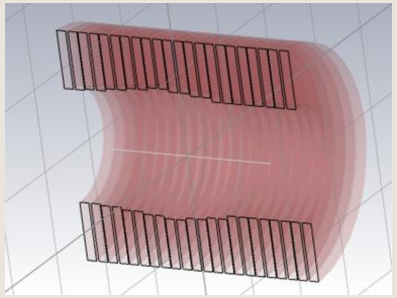
Decelerator — broadband gradient (adiabatic) spin flipper in high magnetic field

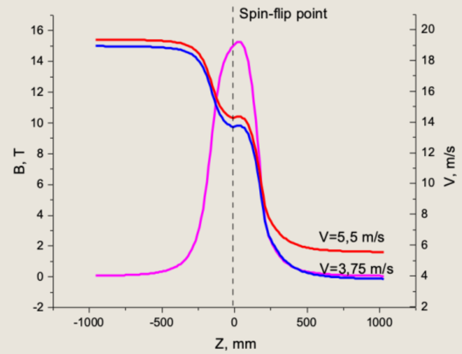




$$\Delta E = 2\mu B = \hbar\omega$$

Preliminary design of stationary gradient field – 15T superconducting solenoid.





The dependence of the magnetic field and neutron velocities from the coordinate along the axis

✓Decelerator reduces the energy of all neutrons by the same amount

✓Time lens is necessary to compensate the dispersion of the time of subsequent deceleration

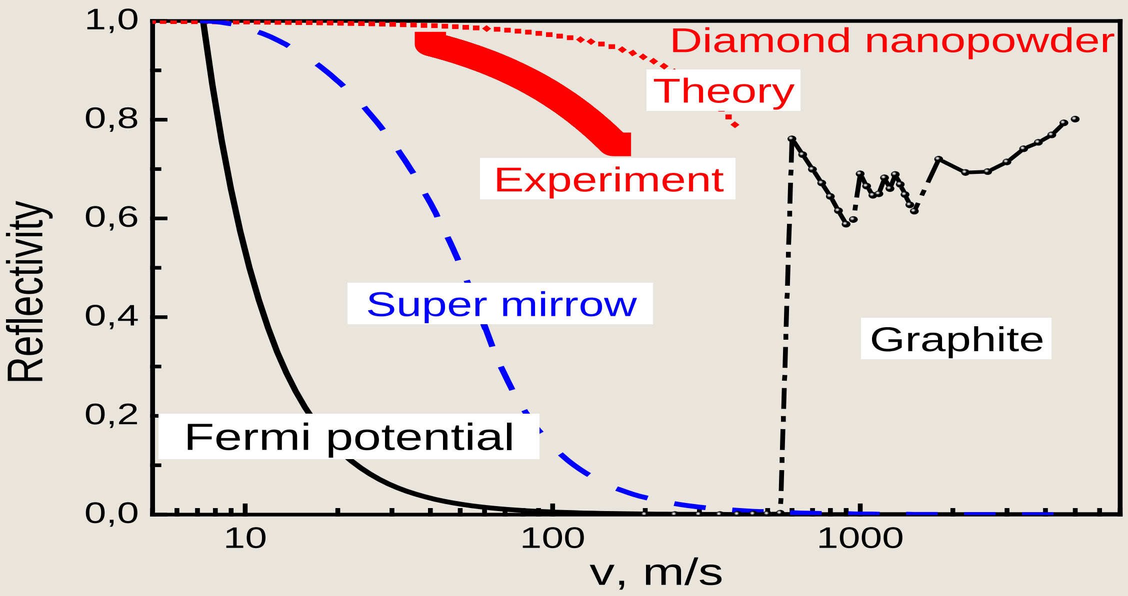
A.I. Frank, G.V. Kulin. *On the duration of the pulse formed by a local time lens for ultracold neutrons*, NIM A **1053** (2023) 168370

A.I. Frank, G.V. Kulin, M.A. Zakharov. *On a New Possibility of Pulsed Accumulation of Ultra Cold Neutrons in a Trap*, Phys. Part. Nuclei Lett. **20** (2023) 664–667

Reflection of Cold Neutrons by Nanoparticles

Efficient elastic reflection of VCN (λ>25Å) at diamond nanoparticle powders (d~ λ)

Nano-diamond trap



Could be used:

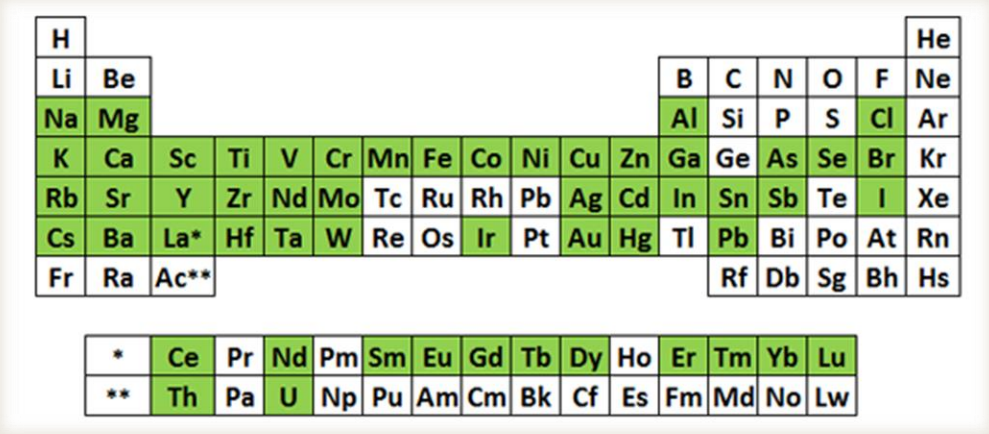
- Storage of very cold neutrons

dozens of times possible increasing neutron density

- Using as reflector in cold neutron souse

dozens of times more intensive VCN and UCN source

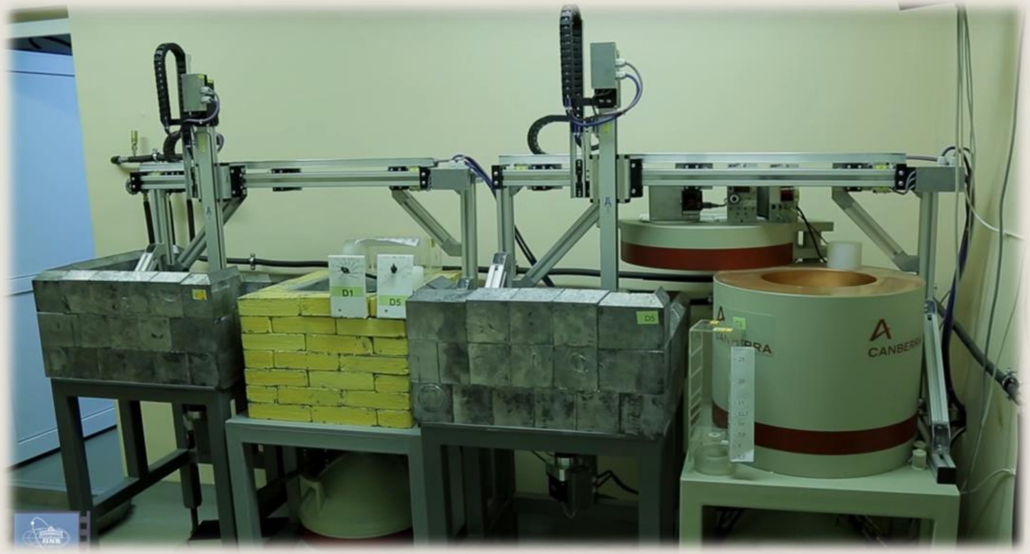
Neutron activation analysis at FLNP



- 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 at REGATA and REGATA-2 facilities

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



Atmospheric Deposition of Trace Elements

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**.

courtesy of Dr. M.V. Frontasyeva

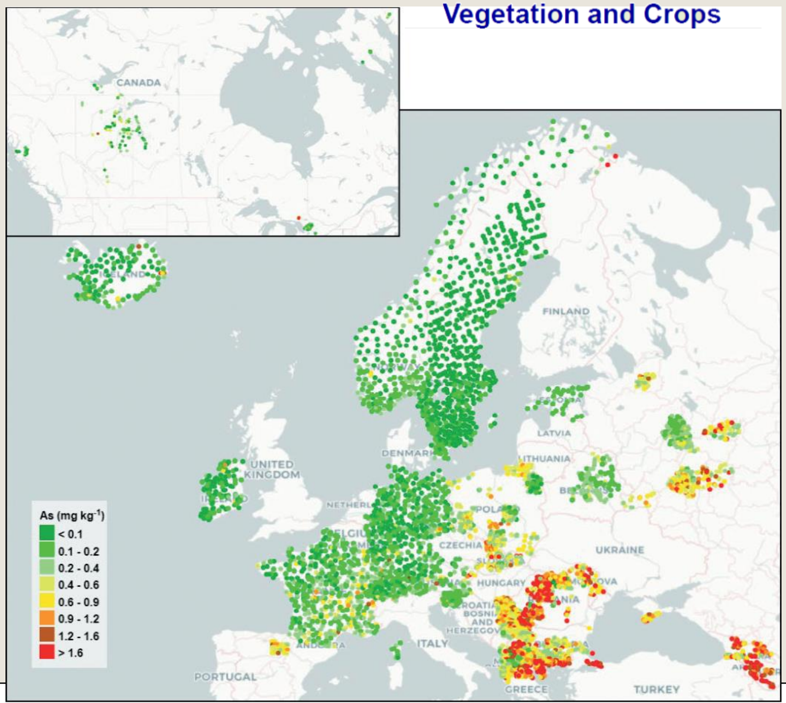
- **Moss** is used as a monitor of **atmospheric pollution** determined using the **Neutron Activation Analysis** detecting **heavy metals** and other trace elements (up to **45** in total)

UNECE

United Nations

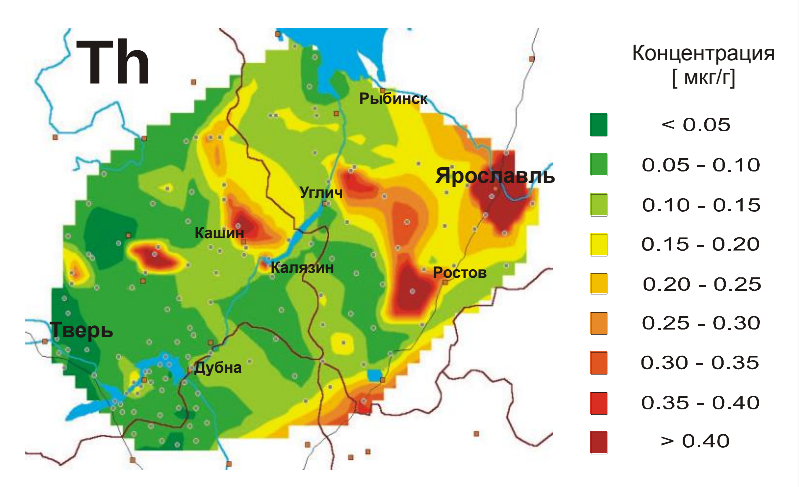
United Nations Economic Commission for Europe

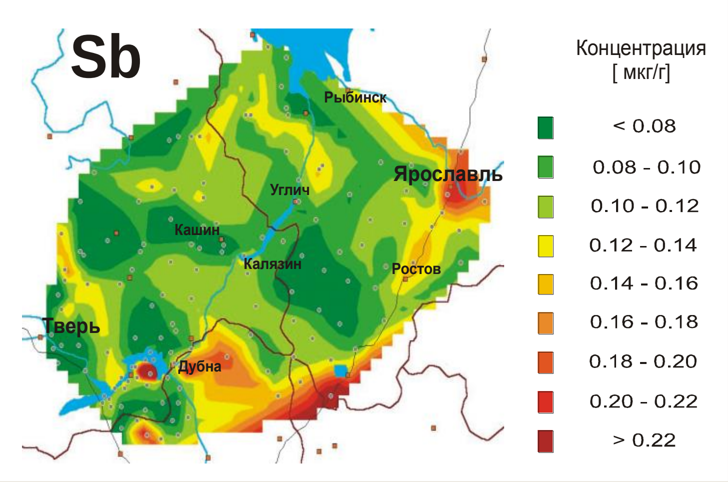
International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops

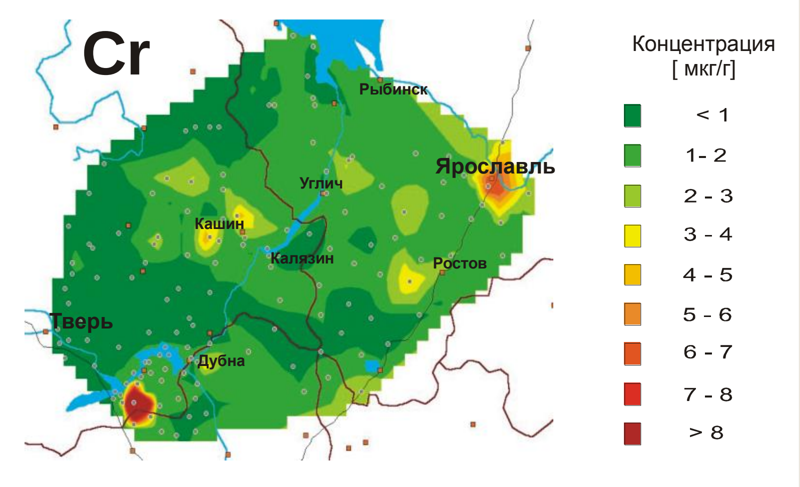


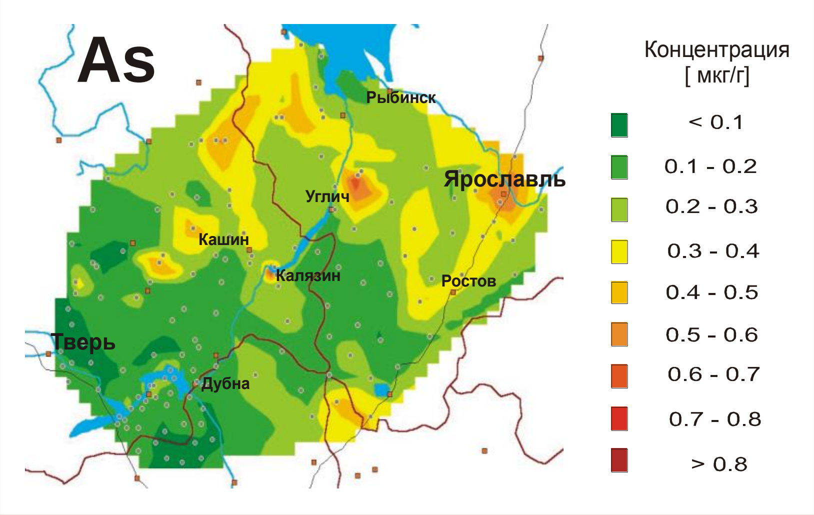
Map of arsenic distribution from the 2015-2016 report

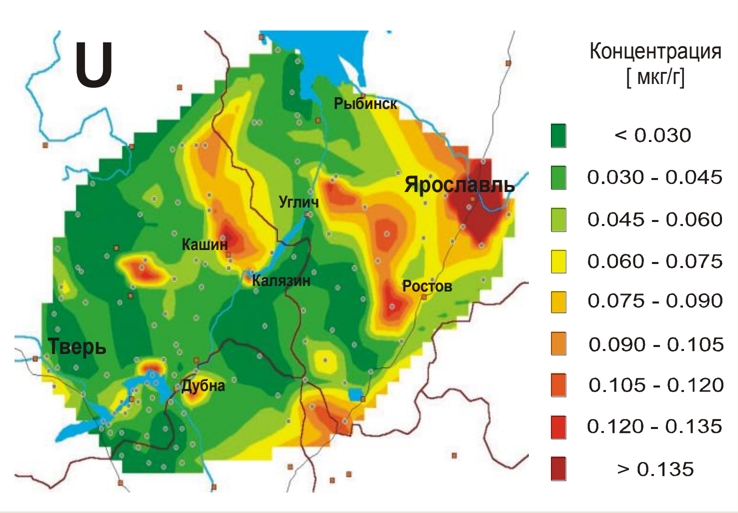
Example of the maps of the element distribution on the investigated territory (Tver' and Yaroslavl' Regions)

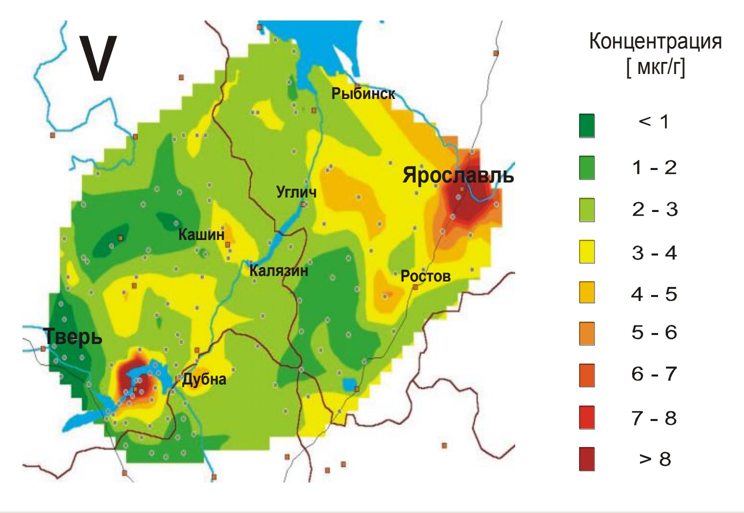




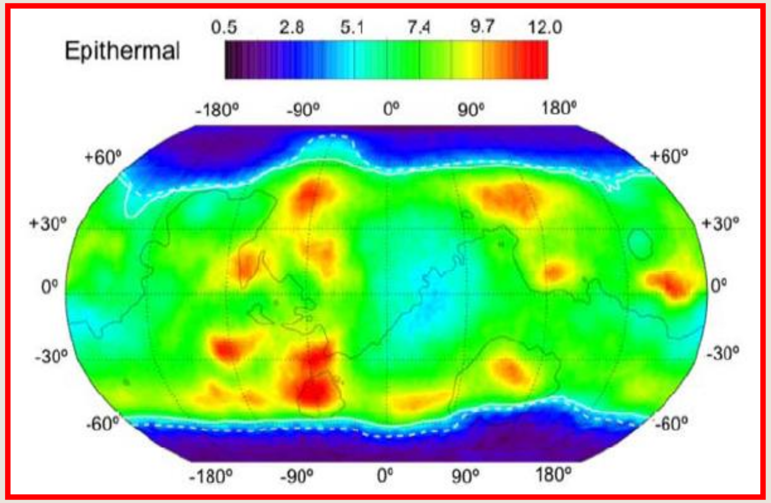


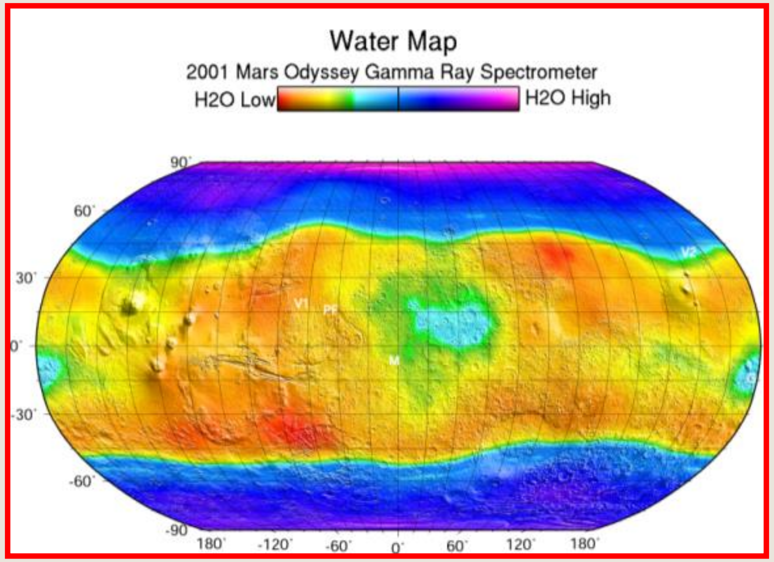


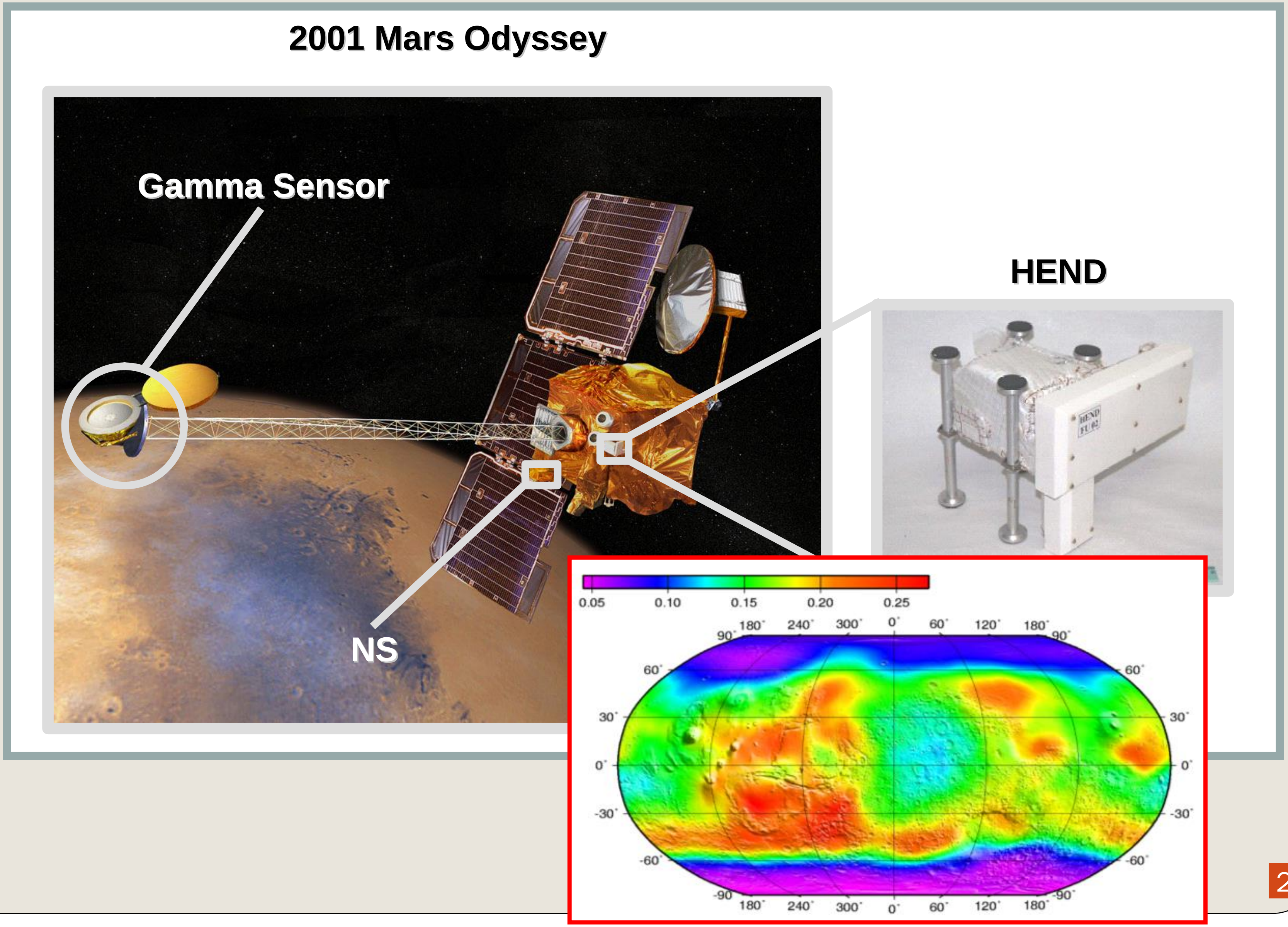




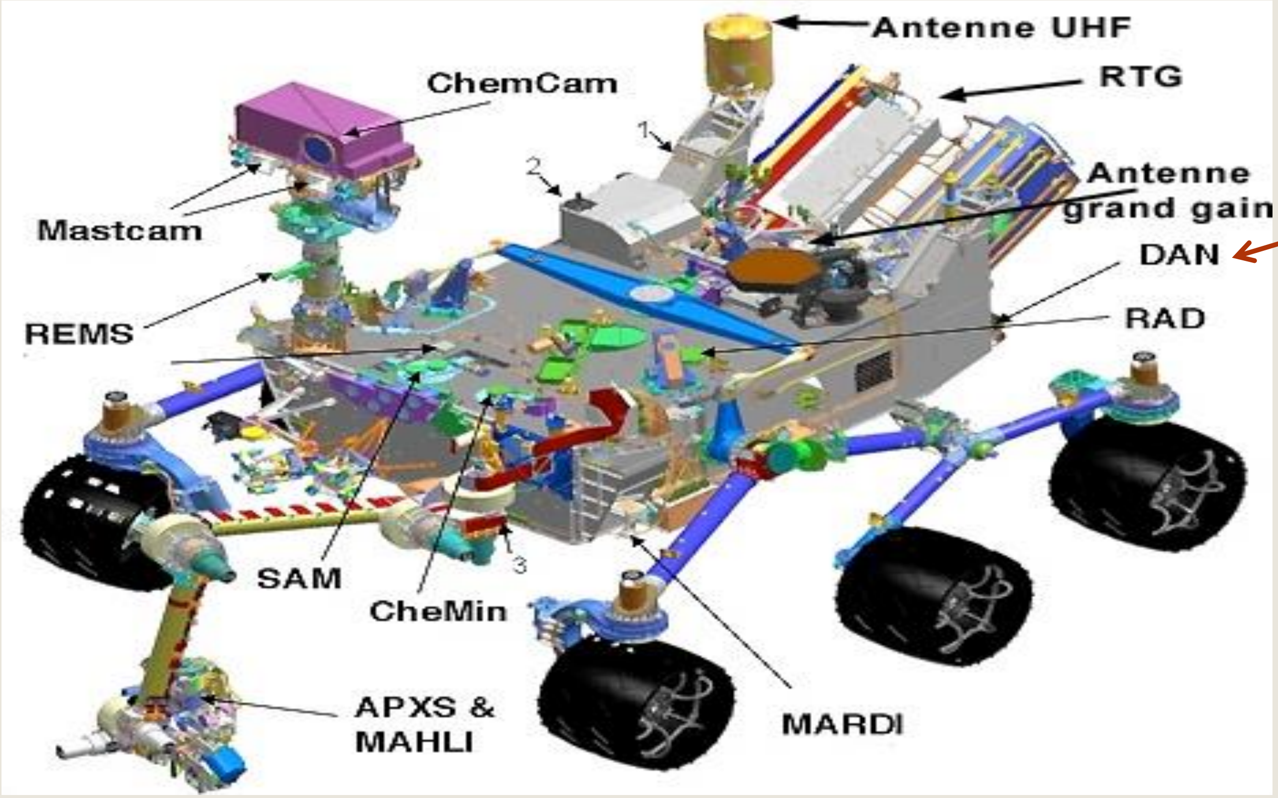
Neutrons in space

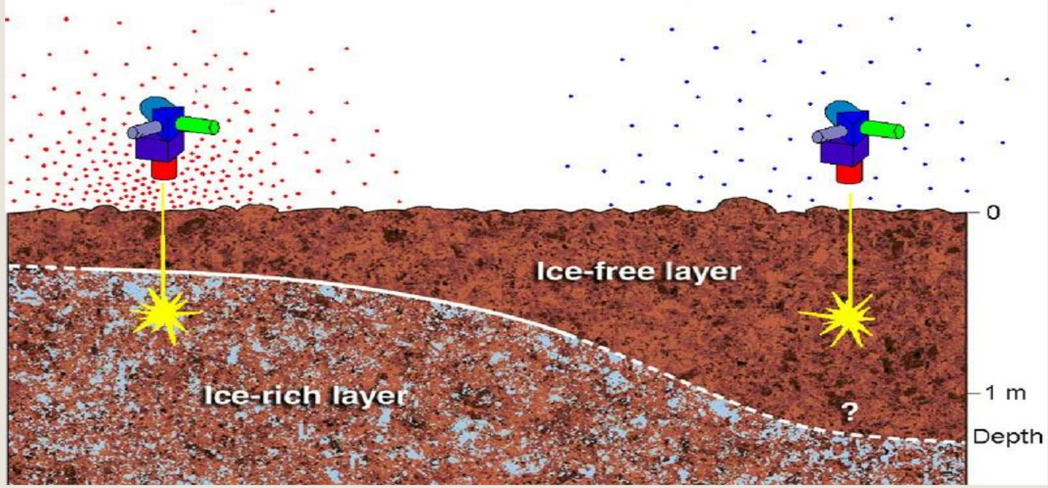






Dynamic albedo of neutrons on Curiosity





Thank you for your attention!

http://ibr-2.jinr.ru
http://flnp.jinr.ru
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