# Tagged neutron method as a tool for nuclear reaction studies and elemental analysis – the TANGRA project

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**for the TANGRA collaboration**

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# TANGRA project
# TAgged Neutrons and Gamma-RAys

**Participants:**

1. *Frank Laboratory of Neutron Physics, JINR, Dubna, Russia*
2. *Veksler and Baldin Laboratory of High Energy Physics, JINR, Dubna, Russia*
3. *Dzhelepov Laboratory of Nuclear Problems, JINR, Dubna, Russia*
4. *Laboratory of Radiation Biology, JINR, Dubna, Russia*
5. *Lomonosov Moscow State University, SINP, Moscow, Russia.*
6. *N.L. Dukhov All-Russian Automation Research Institute, Moscow, Russia.*
7. *Laboratory for Nuclear Analytical Methods, Institute Ruđer Bošković, Zagreb, Croatia*
8. *Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
9. *Banaras Hindu University, Varanasi, India*
10. *University of Alexandria, Egypt*

# Aims of the project

1. **Basic research**

Using tagged neutron beams for experimental investigations in the field of fundamental nuclear physics

- **Investigation of reactions (n,n`$\gamma$) using the tagged neutrons method.**
- Investigation of reactions (n,2n`), (n,n`) using the tagged neutron method.

2. **Applied research**

Development of the tagged neutron method for identification of a wider range of elements and substances

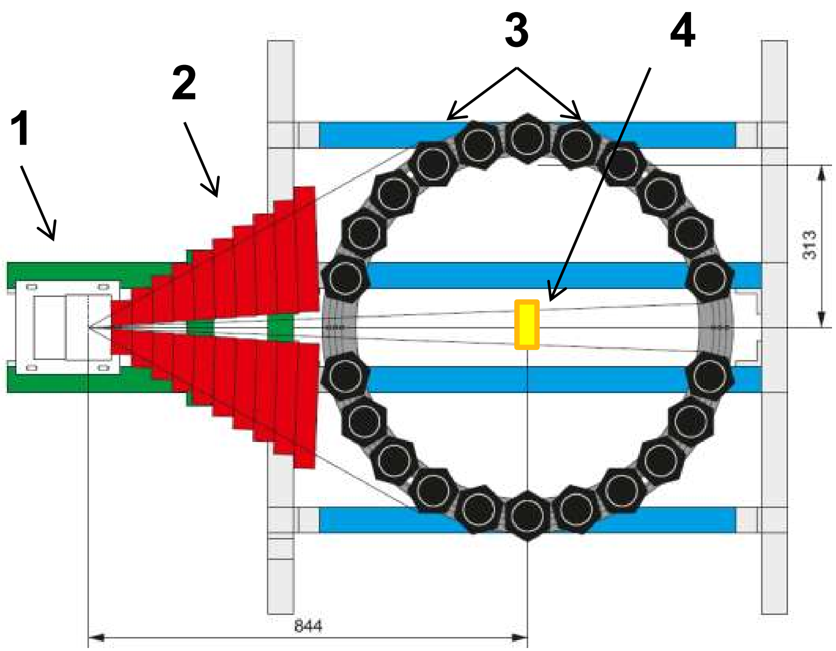
- Development of a database on reaction cross sections for interaction of neutrons with energy 14.1 MeV with nuclei and on the characteristic gamma lines
- Development of methods to study the elemental composition of soils and minerals to determine the content of various elements

3. **Methodical research**

- Development of algorithms for the analysis of experimental data coming from the detectors of neutron and gamma radiation.
- Design and construction of detectors and electronics with improved timing and energy characteristics for use in intense neutron fields.

# Main components of the TANGRA setup

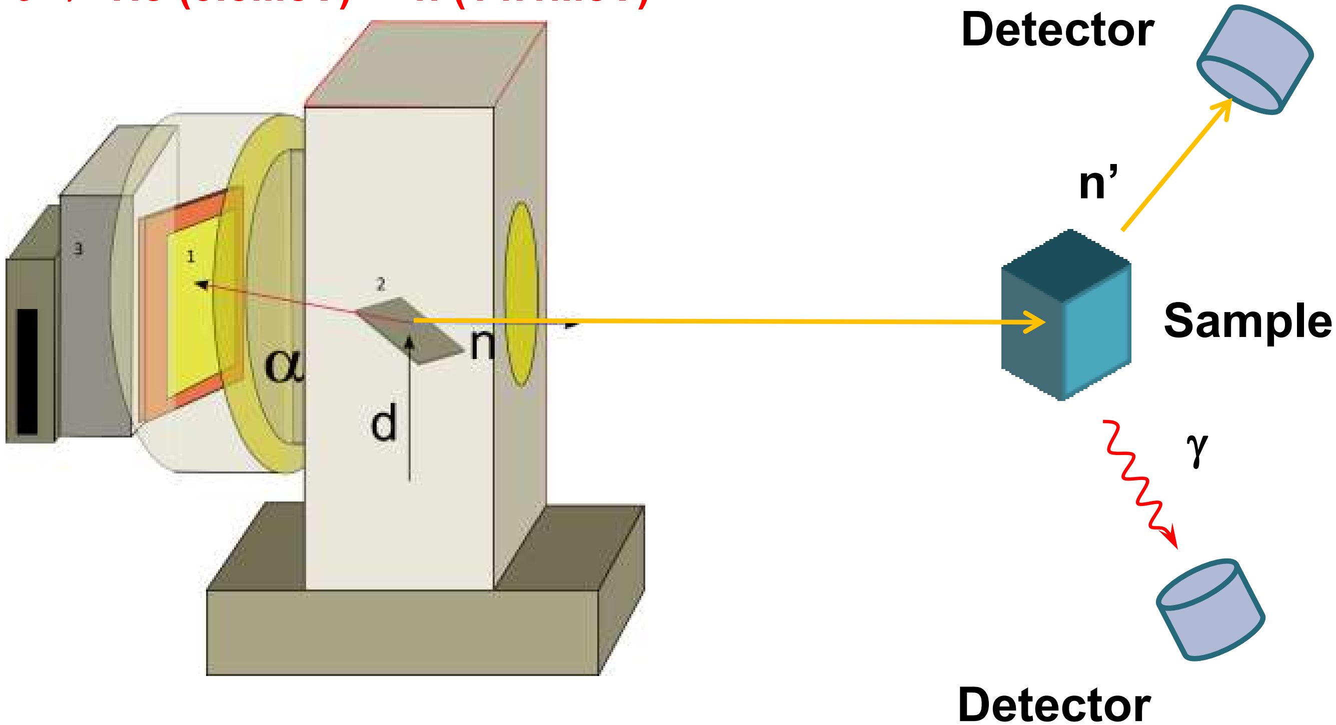
**d + t → $^4$He (3.5MeV) + n (14.1MeV)**




1. **Neutron generator with a position sensitive detector of α-particles**
2. **Shielding (optional)**
3. **Detectors of γ-rays / neutrons**
4. **Sample**

# The Tagged Neutron Method – TNM

$d + t \rightarrow {}^{4}He\ (3.5MeV)\ + n\ (14.1MeV)$

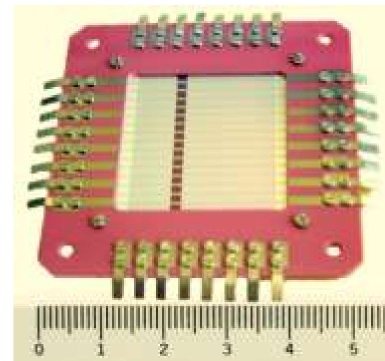



**Neutron generator ING-27**

**Measured quantities:**

- **Pulse height (particle energy)**
- **Time-of-flight (n-gamma separation, background rejection)**
- **Pulse shape (n-gamma separation)**
- **Angle of emission of the incident neutron and secondary particle (neutron or gamma)**

# Neutron generator ING-27



***Produced by N.L. Dukhov All-Russian Automation Research Institute***

| | |
|---|---|
| **Maximal intensity** | **~5x10$^{7}$ c$^{-1}$** |
| **Neutron energy** | **14.1 MэВ** |
| **Neutron radiation mode** | **steady-state** |
| **Power supply** | **200$\pm$5 V** |
| **Maximum power consumption** | **40 W** |
| **Dimentions** | **130x279x227 mm** |
| **Weight** | **8 kg** |
| **Operation time** | **~1000 hours** |
| **Detector of $\alpha$-particles** | **9, 64 or 256-pixel position sensitive silicon detector** |

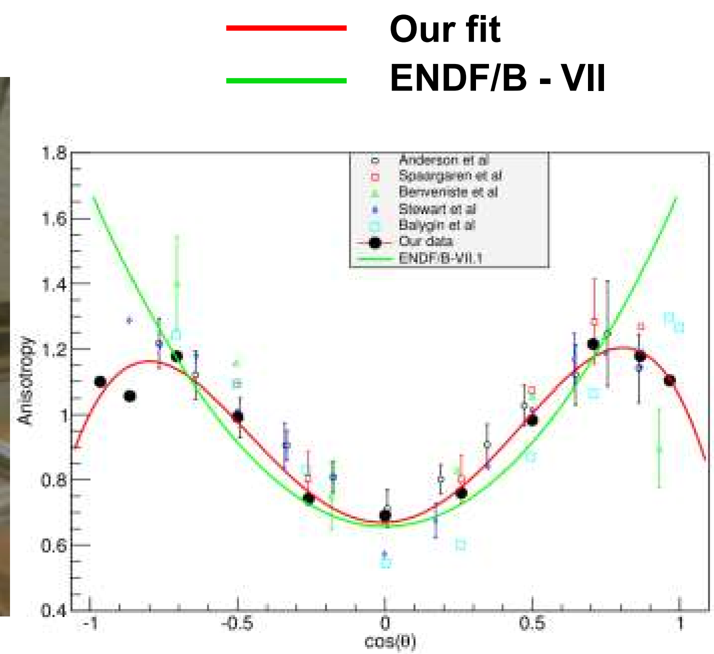
# Main advantages of the Tagged Neutron Method

- Possibility to determine precisely the number of neutrons hitting the target: each neutron is "tagged" by the $\alpha$-detector.
- Information about space and time location of the interaction of the neutron with a target (X,Y-coordinates are given by the pixels of the $\alpha$-detector; Z,t-coordinates are defined by the time-of-flight)
- Due to the selection of a small space-time volume of interaction (voxel) the contribution of background is significantly reduced
- The method allows to identify different elements and substances using their characteristic gamma-rays

# First commissioning experiment at TANGRA

## Measurement of angular distribution of 4.43 MeV γ-rays from 12C(n,n'γ) reaction

**Reported at ISINN23**




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

**a=2.47±0.1**
**b=2.04 ±0.12**

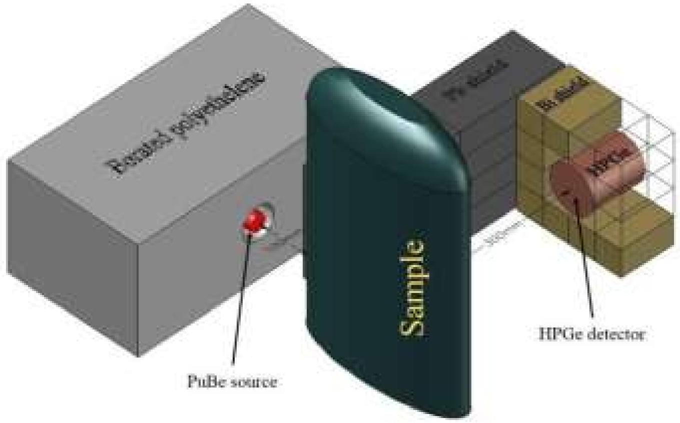
***Anderson et al:***
**a=1.75±0.18**
**b=1.20 ±0.31**

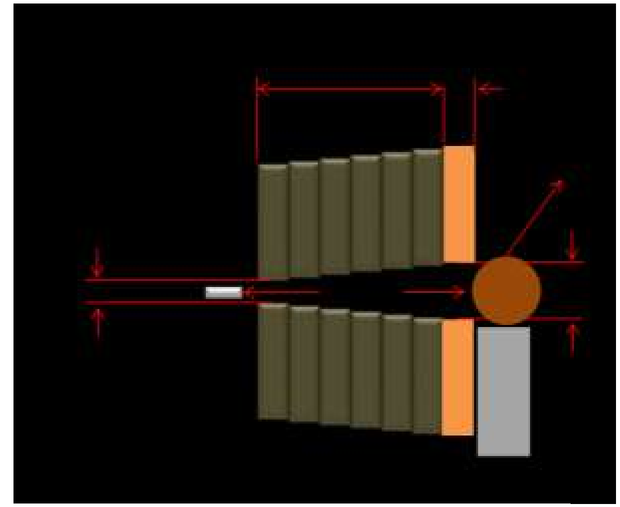
*Yu.N. Kopatch et al, Reported at ISINN-23, Dubna (2015)*
*V. M. Bystritsky et al, Physics of Particles and Nuclei Letters (2016)*

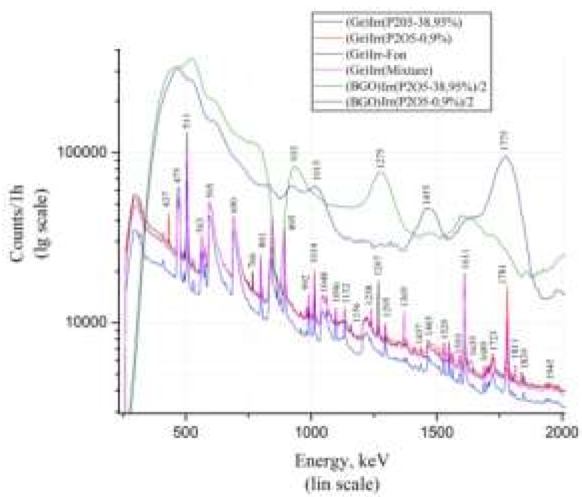
# Applied research at TANGRA

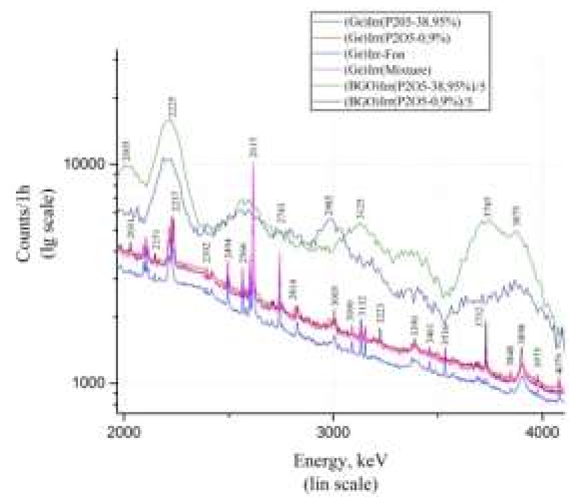
## *Determination of the elemental composition of friable ores*

**Reported at ISINN24**





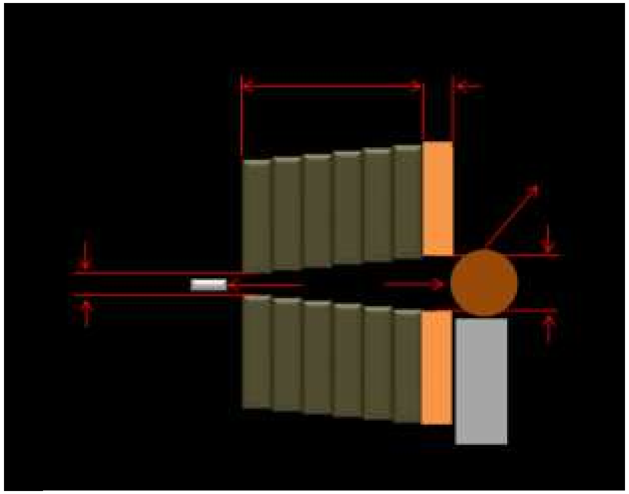




*C.Hramco et al, ISINN-24 Dubna, May 24–27, 2016,JINR, E3-2017-8, p. 157*

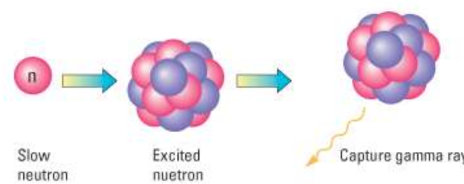
# Applied research at TANGRA

## *Determination of the relative humidity of coke (fuel)*

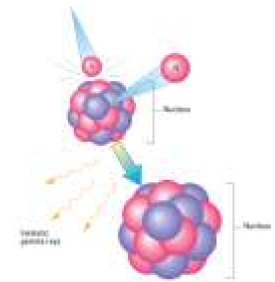
**Reported at ISINN24**

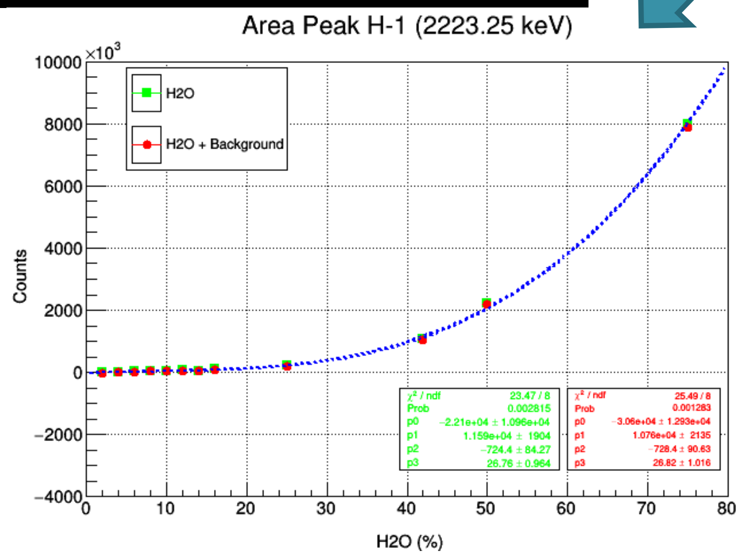


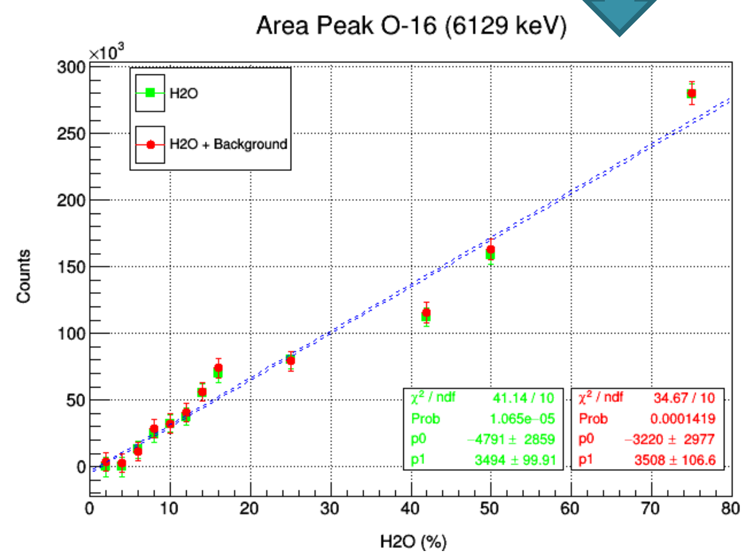
**Neutron capture**




**Neutron inelastic scattering**






*D.Grozdanov et al., Physics of Particles and Nuclei Letters (2017)*

# Methodical works

## *Development of digital electronics and data acquisition systems*

## ADCM-16

**16/32/64-channel digitizers, in the form of one or several PCI-E cards.**

**Sampling frequency** **100 or 66 MHz**

**The digitized signals are transmitted via the PCI-E bus in the computer's memory, where all the data processing and storage takes place.**

**Maximal load of the system is ~ $10^5$ events per second**

# Methodical works

## *Development of digital electronics and data acquisition systems (II)*

**32-channel digital signal recorder – modular device consisting of:**

**1. Mini crate**

**2. One control plate**

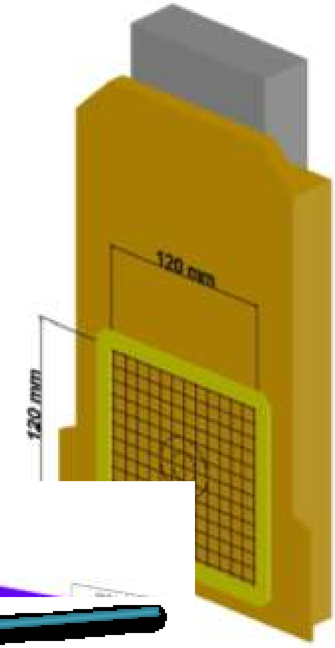
**3. Up to 8 working plates**

- **Each working plate contains 4 independent digitizer channels, 11 bit, 200 Mhz.**
- **Optionally can be replaces by a high resolution 2-channel plate, 16 bit, 100 Mhz**
- **Input signal range: +/- 1 V**
- **Connection to PC through high speed USB-3 port. Maximal data rate – up to 190 Mbytes/sec**
- **Maximal load of the system: ~$10^5$ events/sec for each channel**

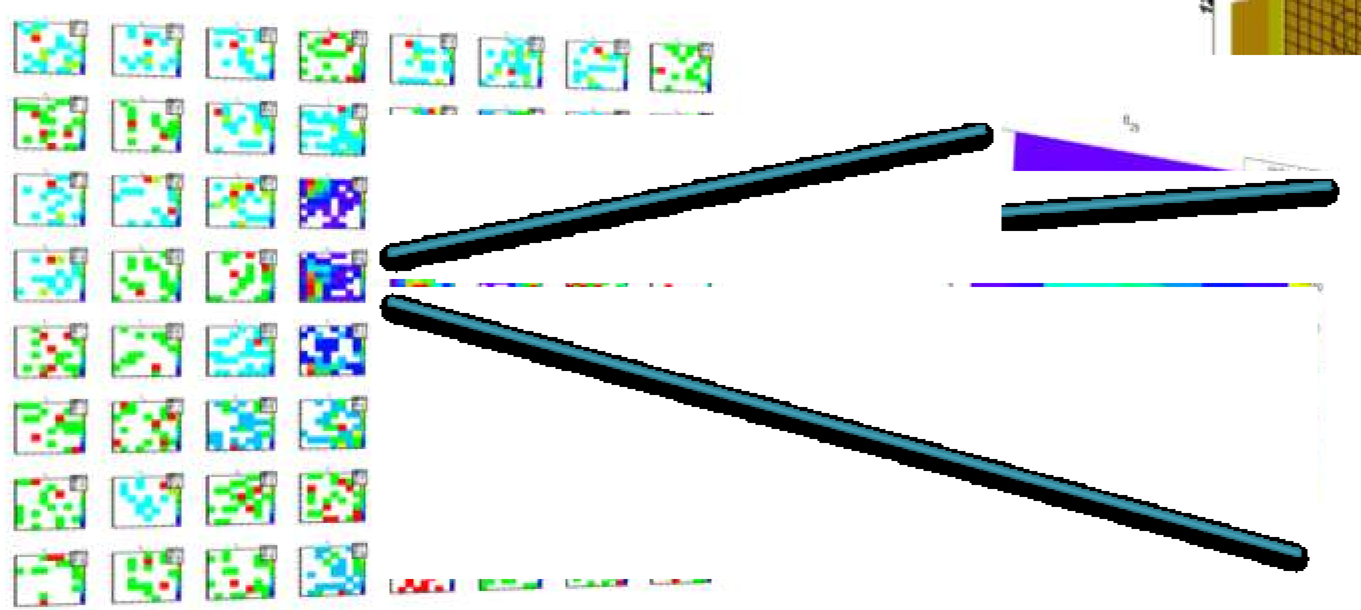
# Methodical works

## *Construction of a silicon two-dimensional position-sensitive fast neutron detector for beam profile measurement*

**2D detector, made of 4 double sided stripped position sensitive Si detectors**



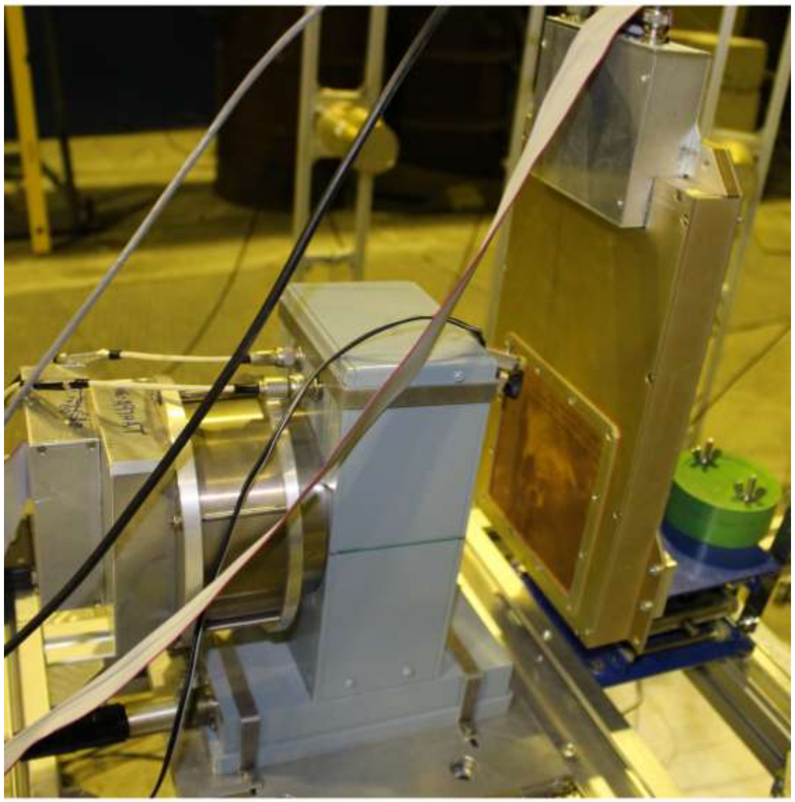

**Each Si detector consists of 32x32 strips ~1.8 mm thick**
**Size of one detector: 60x60mmm**
**Total size: 120x120 mm**
**Thickness: 300 mkm**
**Neutron detection efficiency: ~0.8%**
**At this stage each 8 strips are grouped together forming a matrix 8x8 with a pixel size of ~1.5x1.5 cm**

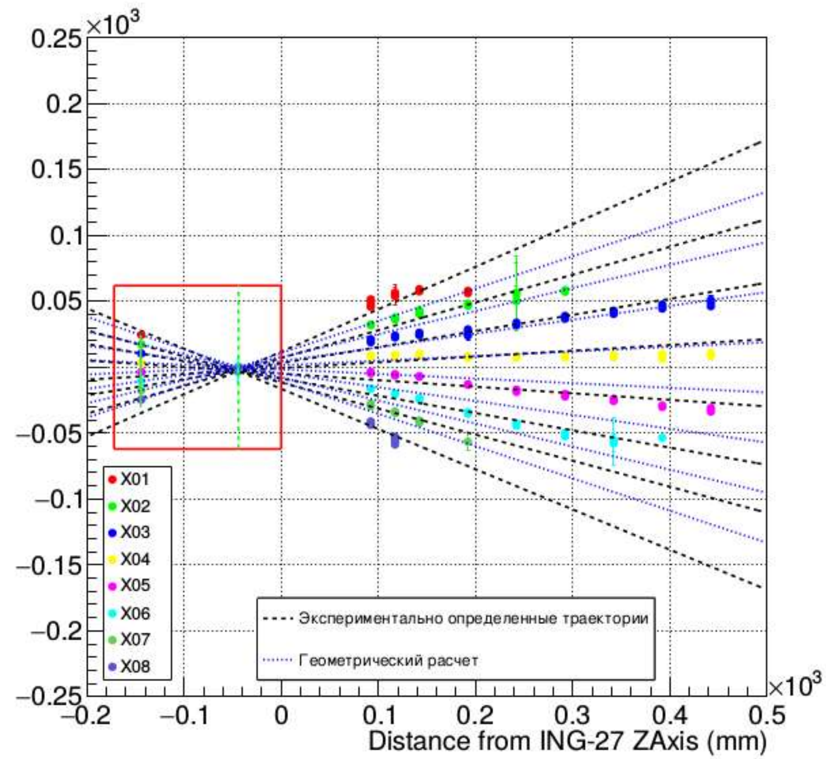


***F.Aliev et al, ireported at SINN-25 Dubna, May 22–26 2017***

# Methodical works

## *Measurements of tagged neutron beams profiles*





# Basic research at TANGRA

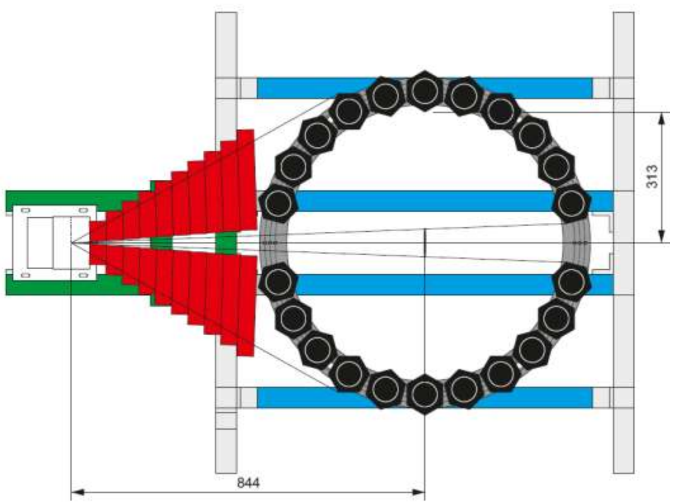
## *Measurement of the angular distribution and partial cross sections of the gamma-rays from inelastic scattering of 14.1 MeV neutrons on nuclei*

### Main points of interest:

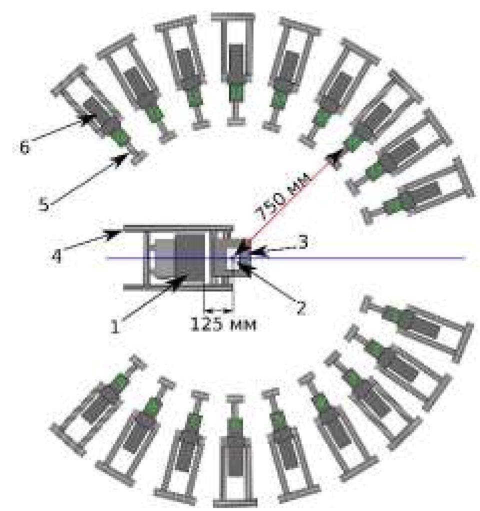
- Eliminate discrepancies between available experimental and evaluated data
- For some nuclei/gamma transitions the gamma-ray anisotropy hasn't been measured at all
- Investigate possible differences between neutron and proton scattering
- Comprehensive theory of angular correlations of gamma-rays from (nn'$\gamma$) reactions doesn't exist
- Angular anisotropy of the emitted gamma-rays has to be taken into account if the tagged neutron method is used for elemental analysis

# Two types of experimental setup for measuring gamma-ray angular correlations

**Stage I: 22 NaI detectors**




**Stage II: 18 BGO detectors**



# Two types of experimental setup for measuring gamma-ray angular correlations

## Samples

### Stage I:

Pb, C, Fe, Bi, Al, $SiO_2$, N

Size - 100x100x50 mm

Placed at a distance of ~850 mm from ING-27

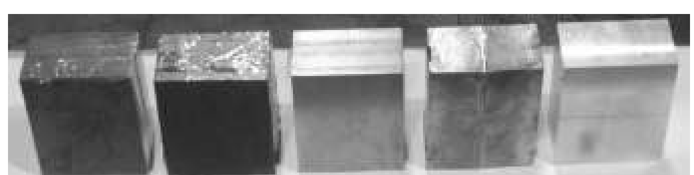
Covered one pixel of the tagged neutron beam

### Stage II:

Ti, Mg, Ca, Zn, Ni, Sn, KCl, NaCl, $MnO_2$

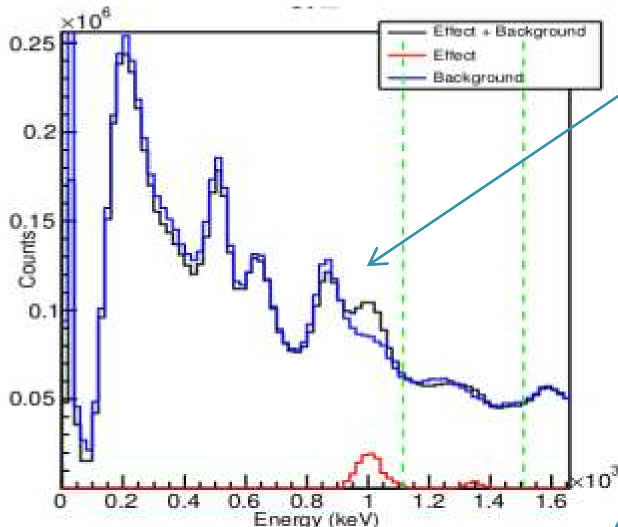
Distance – 125 mm from ING-27

Size – optimized using Monte Carlo calculations with an aim to cover maximal number of tagged neutron beams and minimize the correction for gamma self-absorption
(see report of N.Fedorov)

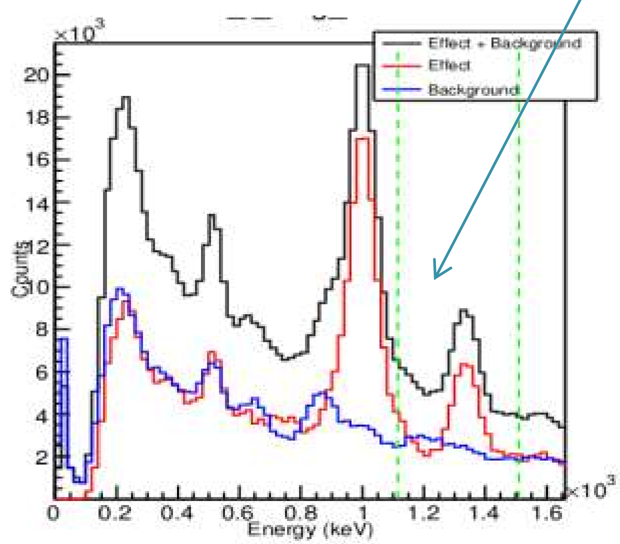


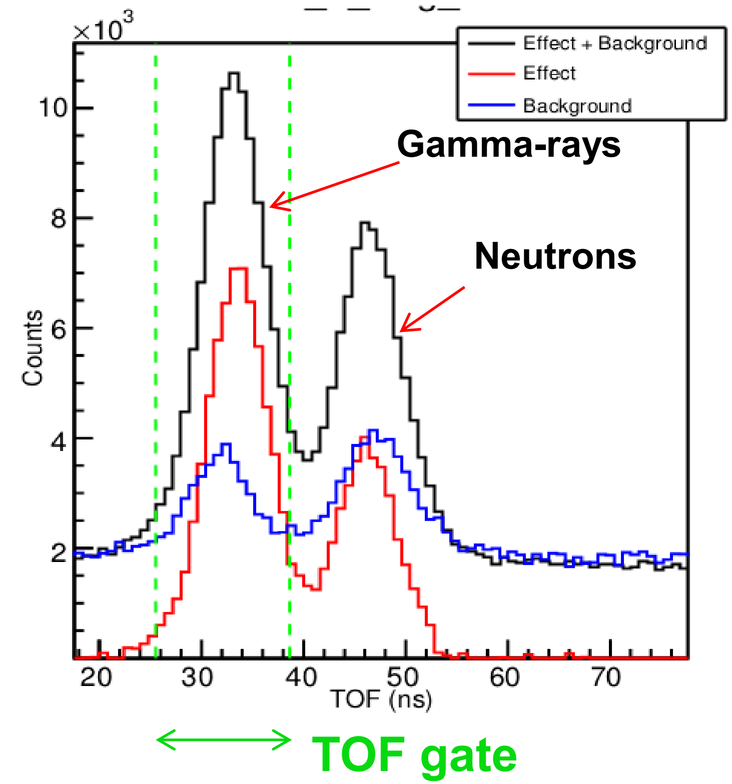
# Energy and time-of-flight spectra from BGO for Ti sample

Energy spectra from the sample (black) and from the background measurements (blue)




The same energy spectra gated on the gamma peak in the TOF spectrum



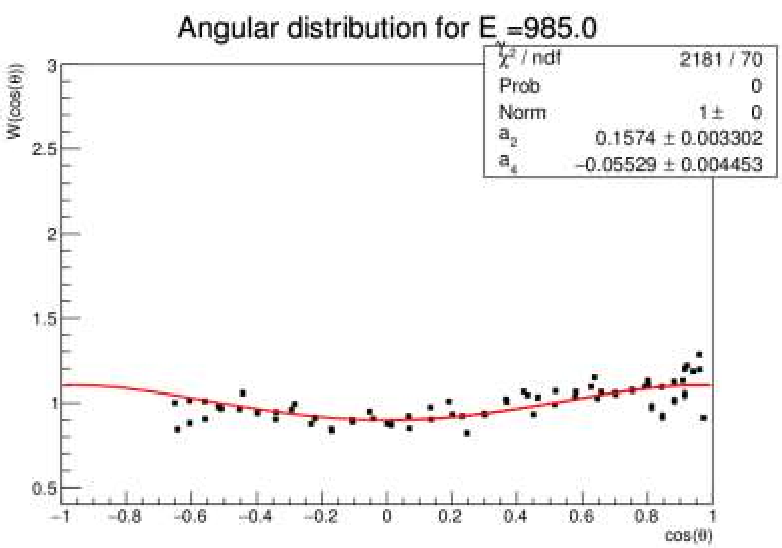



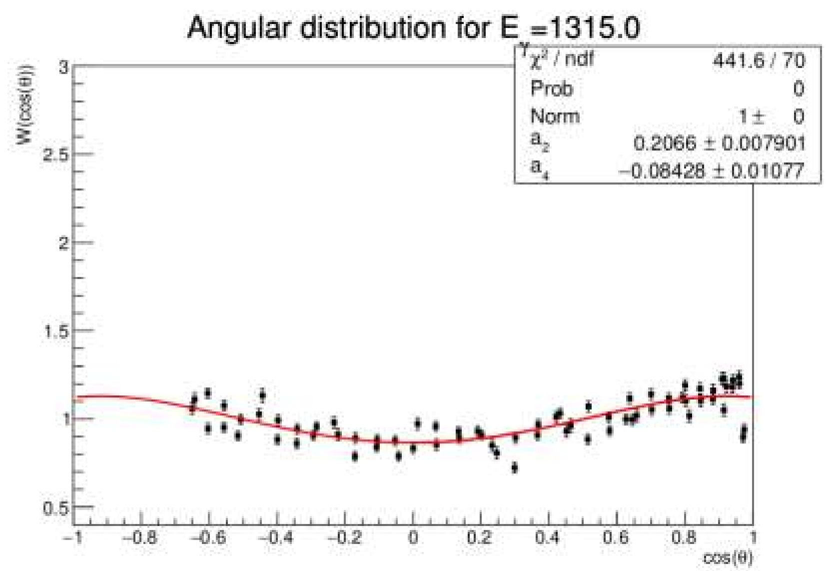
# Angular distributions for two gamma lines of Ti

**Angular distribution is determined as a normalized count rate for each combination of detector – tagged neutron beam**

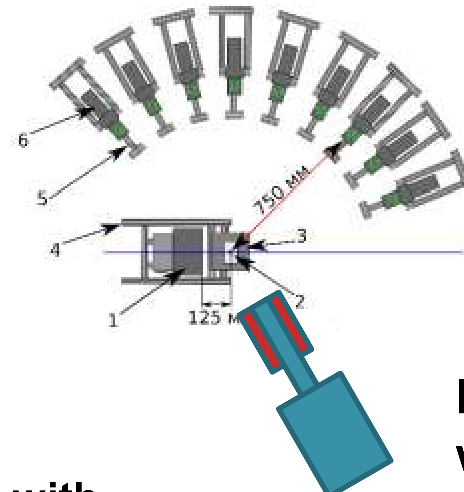
**The measured angular correlation is corrected for the detector efficiency/solid angle and absorption of the gamma-rays in the target (see report of N.Fedorov)**

**The distributions are fitted by the $2^{nd}$ and $4^{th}$ order Legendre polynomials with parameters $a_2$ and $a_4$.**



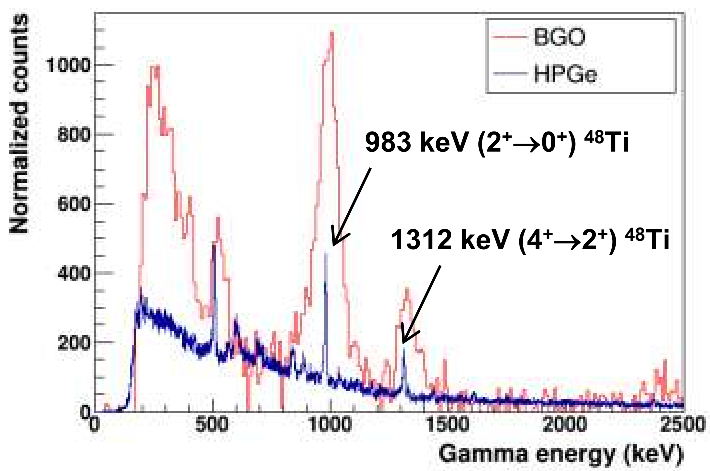
# Measurements of gamma-rays from inelastic scattering of 14.1 MeV neutrons on nuclei using HPGe detector



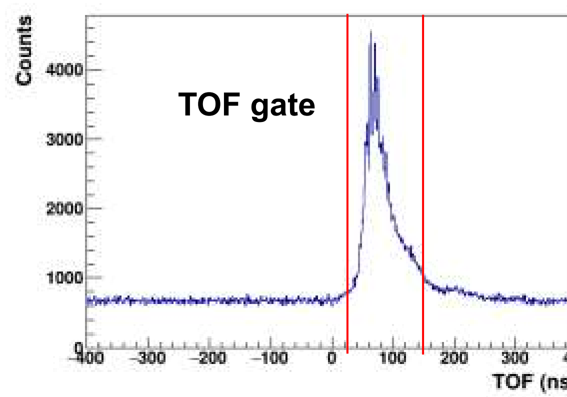

**BGO detectors**

**HPGe detector with shielding**

**Energy spectra for Ti(nn'γ) obtained with BGO and HPGe detectors using TNM**



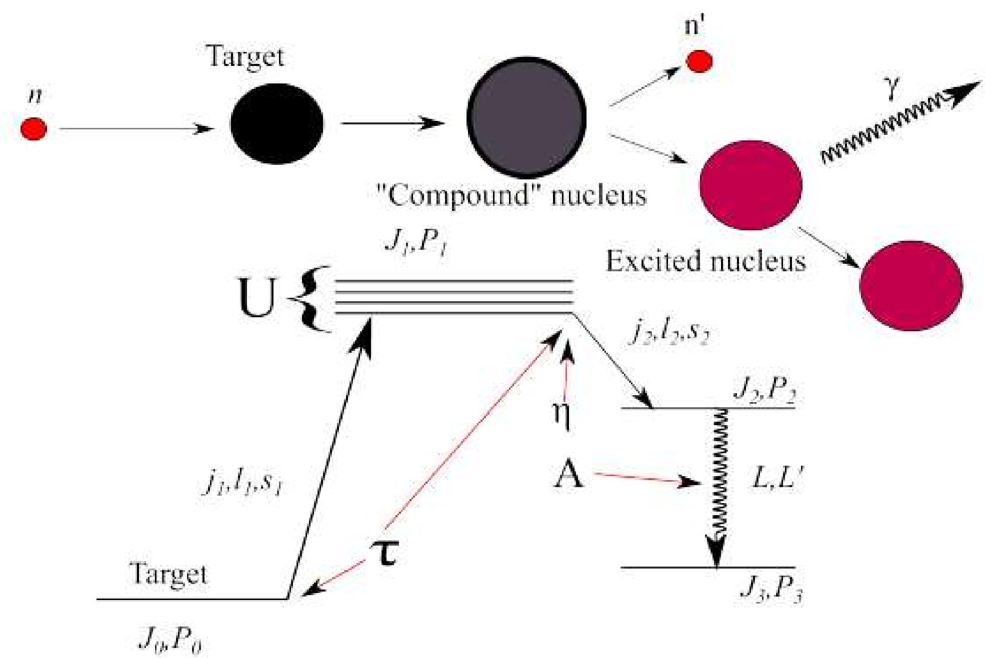

**TOF spectrum from HPGe**



# Future plans

## Development of theoretical models describing angular correlations in the inelastic scattering on 14.1 MeV neutrons on nuclei

**Calculation of the angular distribution of $\gamma$-quanta in the Compound Nucleus framework**

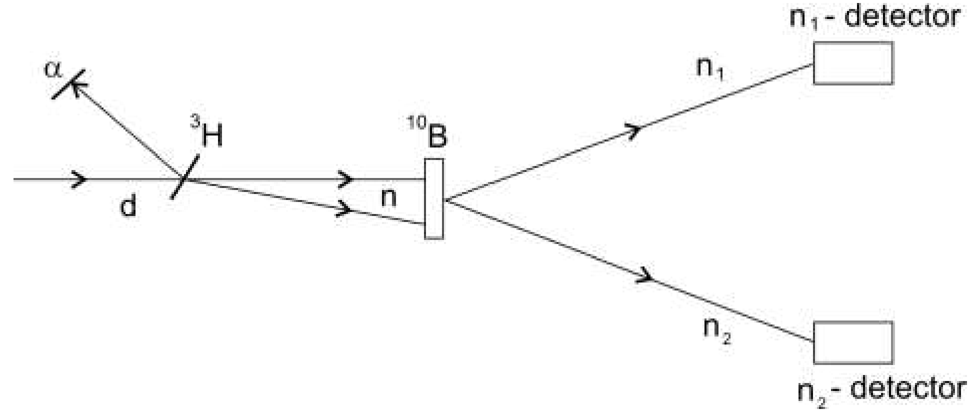



$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\frac{\lambda}{2\pi} \sum_{j_1,J_1,j_2,L',v} g\eta_v(j_1, j_1, J_0, J_1)\times$$
$$\times U_v(j_2, j_1, J_1, J_2)A_v(L, L', J_3, J_2)\tau P_v(\cos(\theta)) \quad (1)$$

- ***N.Fedorov, reported at ISINN-25, May 22-26 2017, Dubna***
- ***N.Fedorov, Master Thesis, 2017***

# Future plans

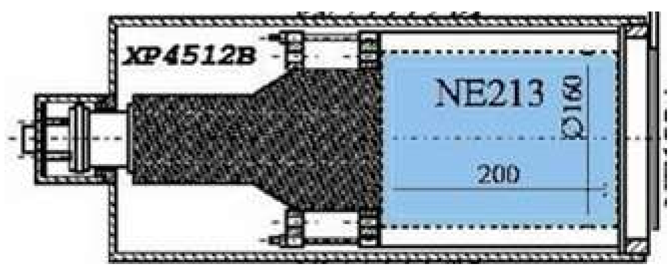
## Investigation of the (n,2n`) and (n,n`) – reactions using the tagged neutron method




**Investigation of the reaction $^{10}B(n,2n)^{9}B \rightarrow p + {}^{8}Be$.**

**<u>Aim:</u>** ***Obtaining information about the low-lying levels of the unstable nucleus $^{9}B$***

**<u>Method:</u>** ***Measurement of the energies of two neutrons using time of flight and calculation of missing-mass spectrum for $^{9}B$.***




***Using high efficiency DEMON detectors with n-gamma separation capability***

# Summary

• The project aimed at the experimental investigations in the field of basic and applied nuclear physics using tagged neutron beam is being realized at JINR Dubna

• Collecting and processing of the experimental data on inelastic scattering on 14.1 MeV neutrons on nuclei is currently taking place at the TANGRA experimental facility.

**Future tasks to do:**

1. Conduction of measurements of characteristic gamma-spectra for various elements. Creation of data-base for element identification.
2. Measuring the cross-sections of (n,2n), (n,n’) reactions on important for nuclear science isotopes.
3. Development of the technique for determining the elemental composition of soils and minerals.

# *Thank you for your attention*