Development of the tagged neutron method for elemental analysis and nuclear reaction studies – TANGRA project

Yu.N. Kopatch

Joint Institute for Nuclear Research

for the TANGRA collaboration

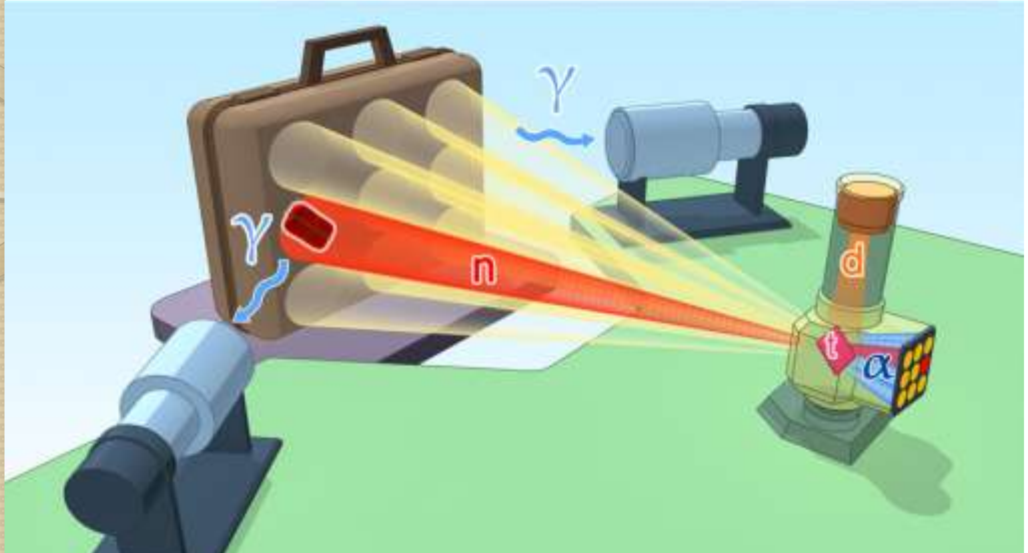
TANGRA – TAgged Neutrons & Gamma RAys

Participants:

Borzakov S., Gundorin N., Dubasov P., Zeynalov Sh. Zontikov A., Kopatch Yu., Rogachev A., Pikelner L., Sedyshe P., Skoy V., Shvetsov V. (1)
Alexakhin, V., Zamyatin N., Zubarev E., Rapatskiy V., Rogov Yu., Salmin R., Sapozhnikov M., Slepnev V., Khabarov S. (2)
Bystritsky V., Krasnoperov A., Sadovsky A., Salamatin A. (3)
Krylov A., Timoshenko G. (4)
Valkovic V., Obhodas J., Sudac D. (5)
Bogolubov E., Ryzhkov V., Khasaev T., Chuprikov A., Yurkov D. (6)
Garanin V., Pautov L., Skvortsova V. (7)
Grozdanov D., Ivanov I., Madjarsky T., Ruskov I., (8)

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. ***N.L. Dukhov All-Russian Automation Research Institute, Moscow, Russia.***
6. ***Lomonosov Moscow State University, Faculty of Geology , 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***

Tagged Neutrons Method – TNM



$d + {}^3H \rightarrow {}^4He\ (3.5MeV) + n\ (14.1MeV)$

Main components:

- **Neutron generator**
- **Position sensitive detector of α-particles**
- **Detectors of γ-rays / neutrons**

The method is successfully used for detection of hazardous substances

We propose to utilize the method for basic and applied nuclear physics studies

Main advantages of the method:

- **Precise determination of the number of neutrons hitting the target: each neutron is "tagged" by the α-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 α-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**

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`γ) 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

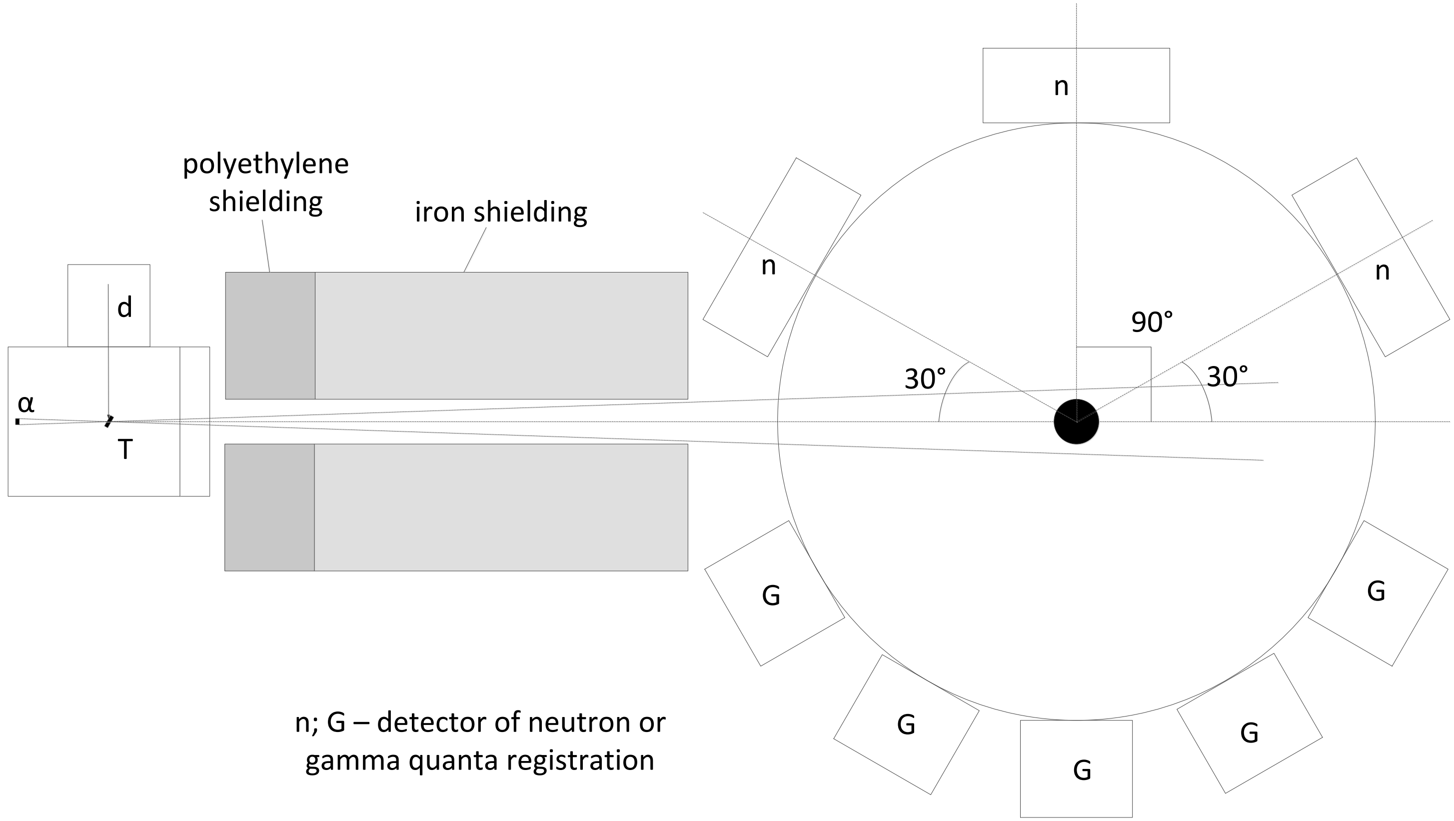
Development of methods to study the elemental composition of soils and minerals to determine the content of various elements

3. Methodical research

Design and construction of gamma and neutron detectors with improved timing and energy characteristics for use in intense neutron fields.

Development of algorithms for the analysis of experimental data coming from the detectors of neutron and gamma radiation.

Schematic diagram of the experiments



- **Neutron generator with built-in detector of α-particles**
- **Detectors of gamma-rays**
- **Detectors of neutrons**
- **Read-out electronics and data acquisition system**

Available

- **Targets**
- **Shielding**

Required

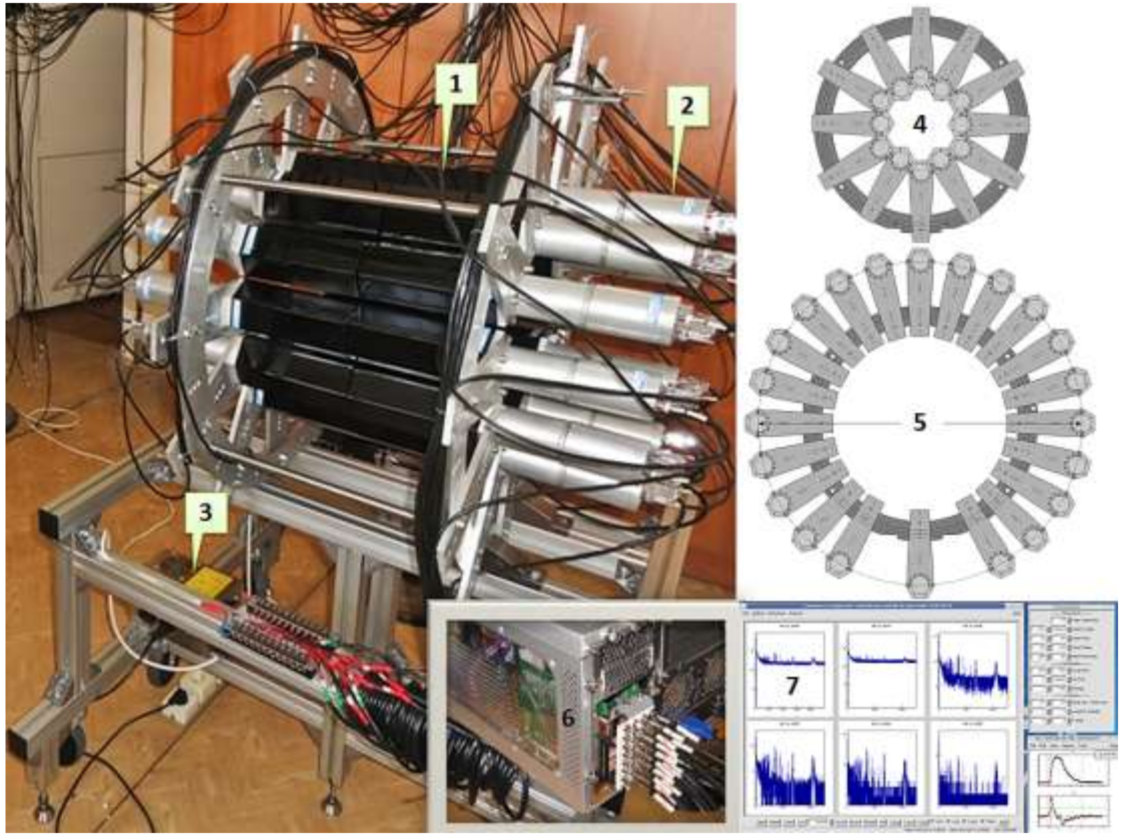
Neutron generator ING-27

Produced by

N.L. Dukhov All-Russian Automation Research Institute

Maximal intensity	~$5 \cdot 10^{7}$ c^{-1}
Neutron energy	14.1 МэВ
Neutron radiation mode	steady-state
Power supply	200±5 V
Maximum power consumption	40 W
Dimentions	130x279x227 mm
Weight	8 kg
Operation time	~800 hours
Detector of α-particles	9-pixel or 64-pixel position sensitive silicon detector

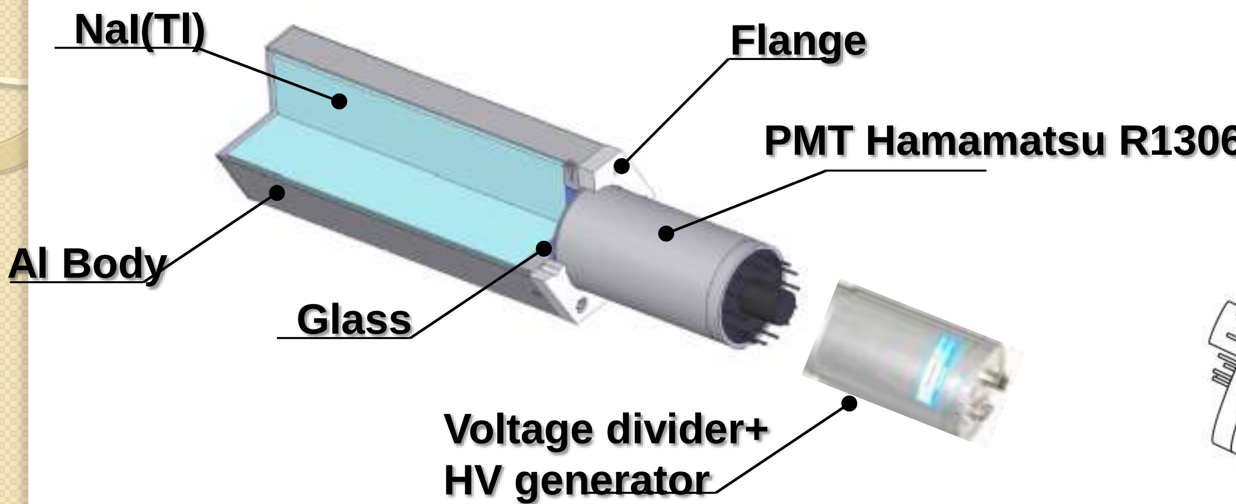
Multidetector system «Romashka»

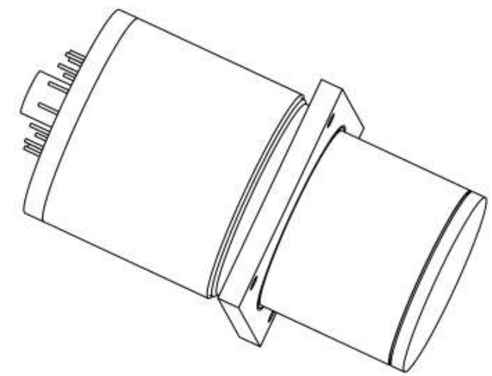


24 NaI (Tl) scintillation counters, hexagonal shape, size 78x90x200.

Energy resolution at 662 keV – ~8%
Time resolution ~3nsec

Gamma-ray detectors





NaI 78x90x200 mm

BGO ∅76x65 mm

Energy resolution at 662 keV: ~7-9%

Time resolution: ~3 нсек

Neutron detectors

- detectors based on liquid scintillator BC501 (Saint Gobain company), the size of the scintillator ∅ 125x50 mm (2 pcs);
- detectors based on liquid scintillator NE-213 (DEMON detectors), the size of the scintillator ∅ 160x200 mm (2 pcs);
- detectors based on plastic P-terphenyl, the size of the scintillator ∅70x50 mm (4 pcs)
- detectors based on stilbene crystals (AMCRYS company), the size of the scintillator ∅ 76x50 mm (2 pcs.)

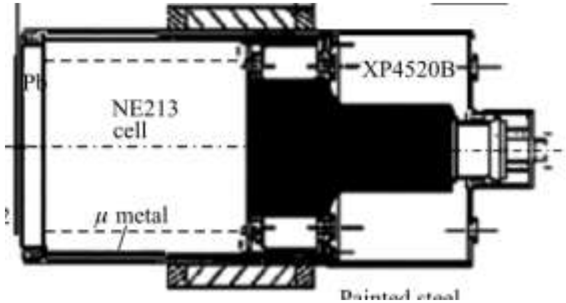
It is planned to acquire additional neutron detectors

All of the above fast neutron detectors can effectively separate neutrons from gamma rays by the pulse shape

Neutron detectors

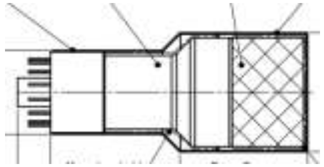
- DEMON detector:

∅ 16 x 20 cm NE-213

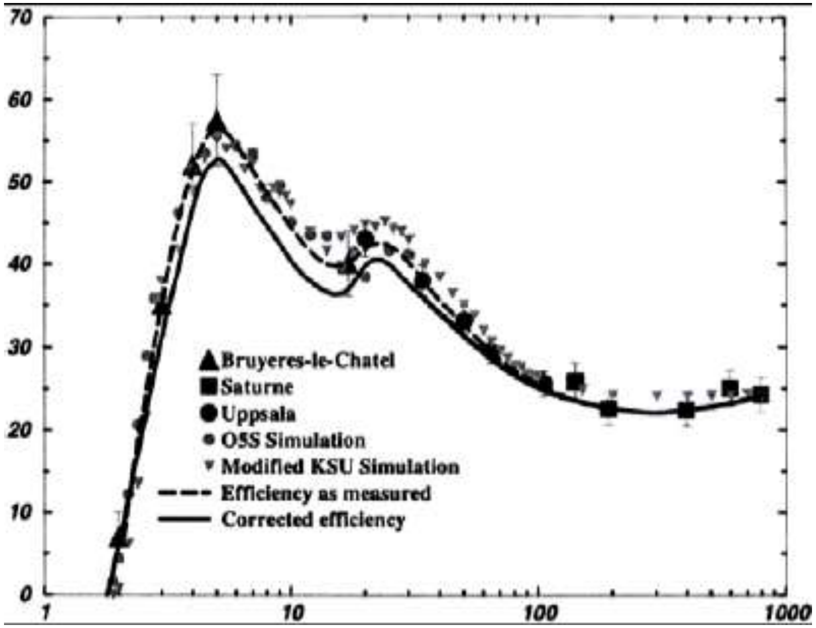


- **Stilbene detector**

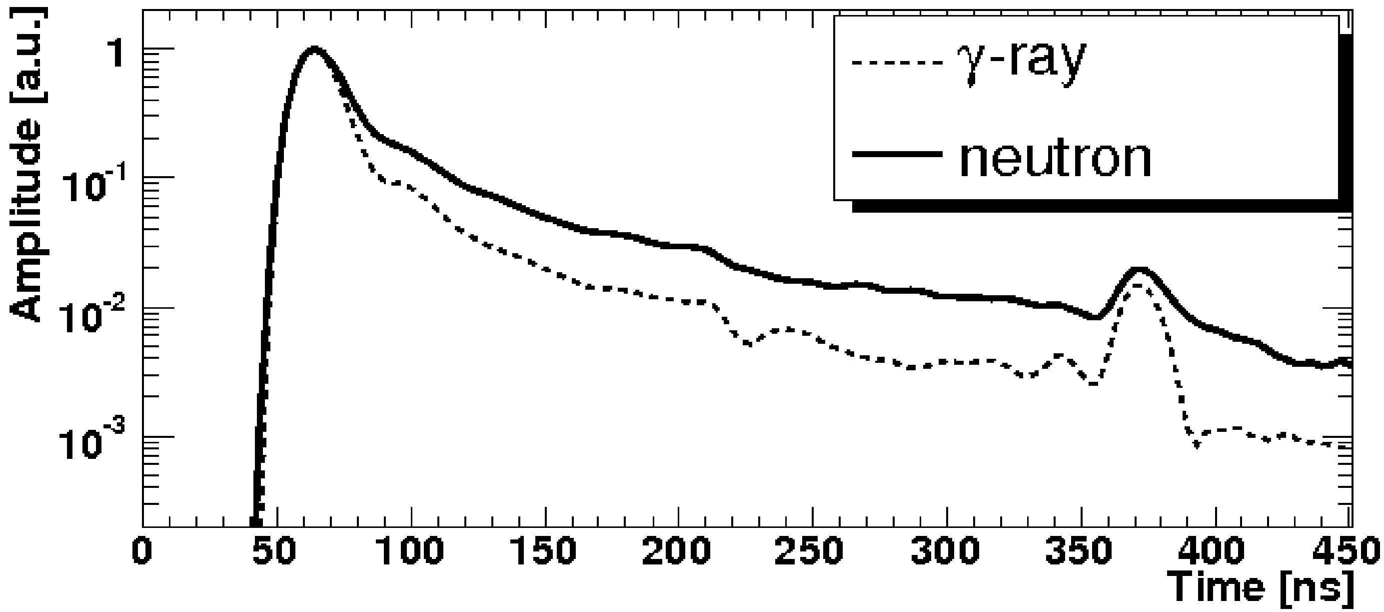
∅ 7.6 x 5 cm stilbene



Neutron detection efficiency of the DEMON detector as a function of neutron energy

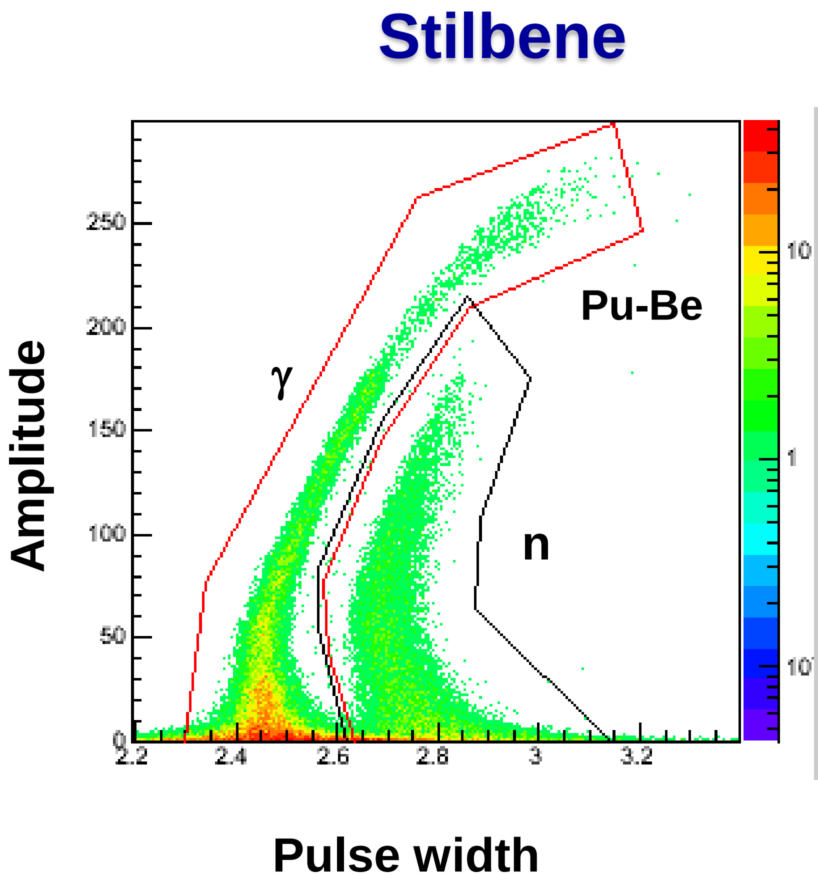


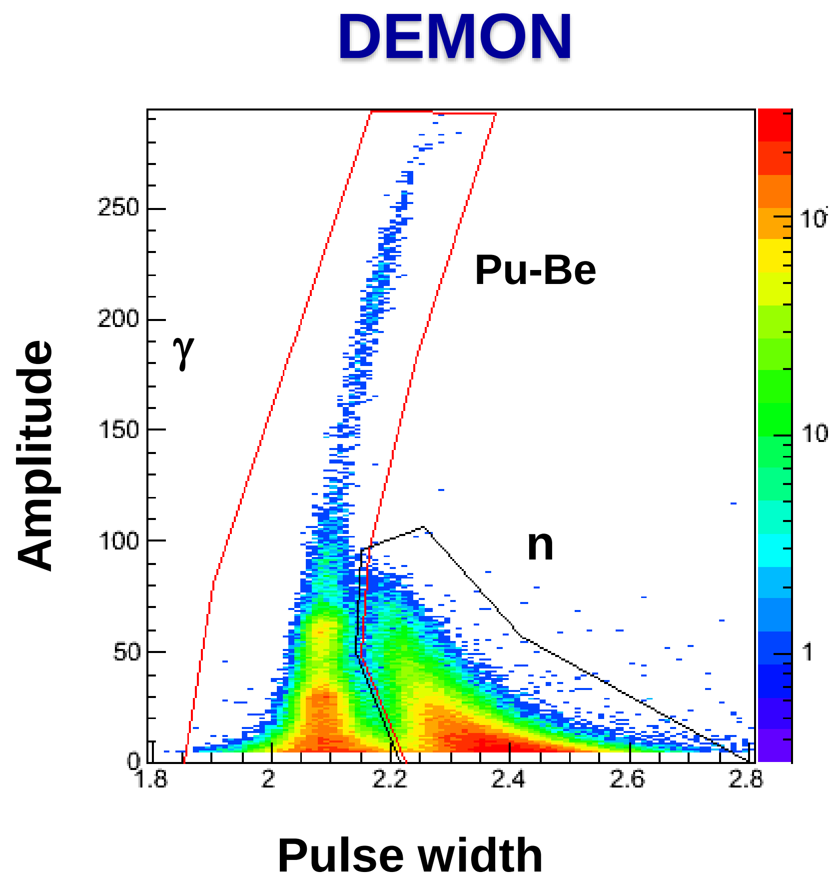
Pulse-shape –gamma separation



- The main process of the neutron interaction with the detector substance for energies i~ 1 - 20 MeV is the elastic scattering on hydrogen.
- Recoil protons excite slower scintillation components, which results in a longer “tail” of the pulse, compared to the electron-induced scintillation.

Pulse-shape n-gamma separation spectra for the neutron detectors





Electronics and data acquisition

ADCM-16

16/32/48-channel digitizers, in the form of one or several PCI-E cards.

Sampling frequency 100 MHz

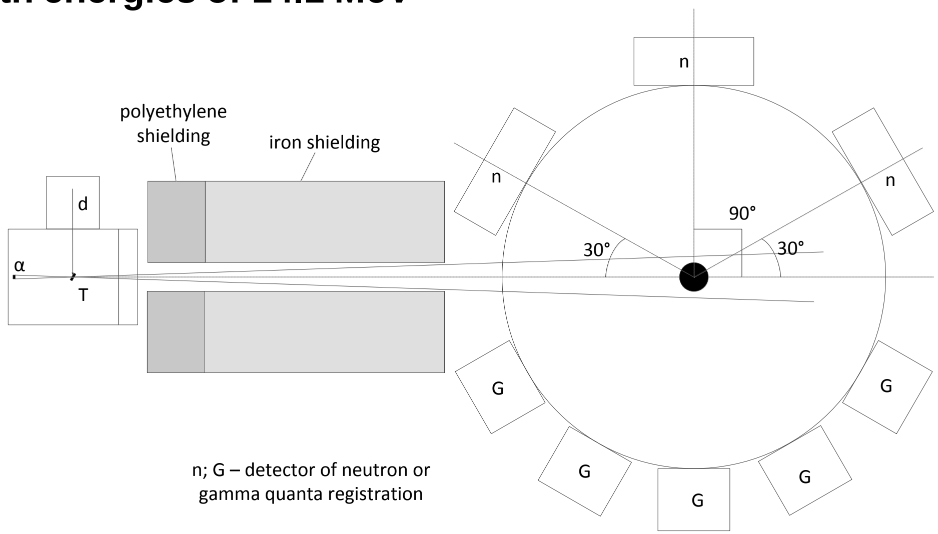
The digitized signals are transmitted via the PCI-E bus in the computer's memory, where all the data processing and storage takes place.

Maximum load of the system is ~ 10^5 events per second

Experimental program: basic research

1. Investigation of the (n,n\`γ)- reactions using the tagged neutron method

It is proposed to set up an experiment to study the reaction ^{12}C (n, n \`γ) ^{12}C by neutrons with energies of 14.1 MeV

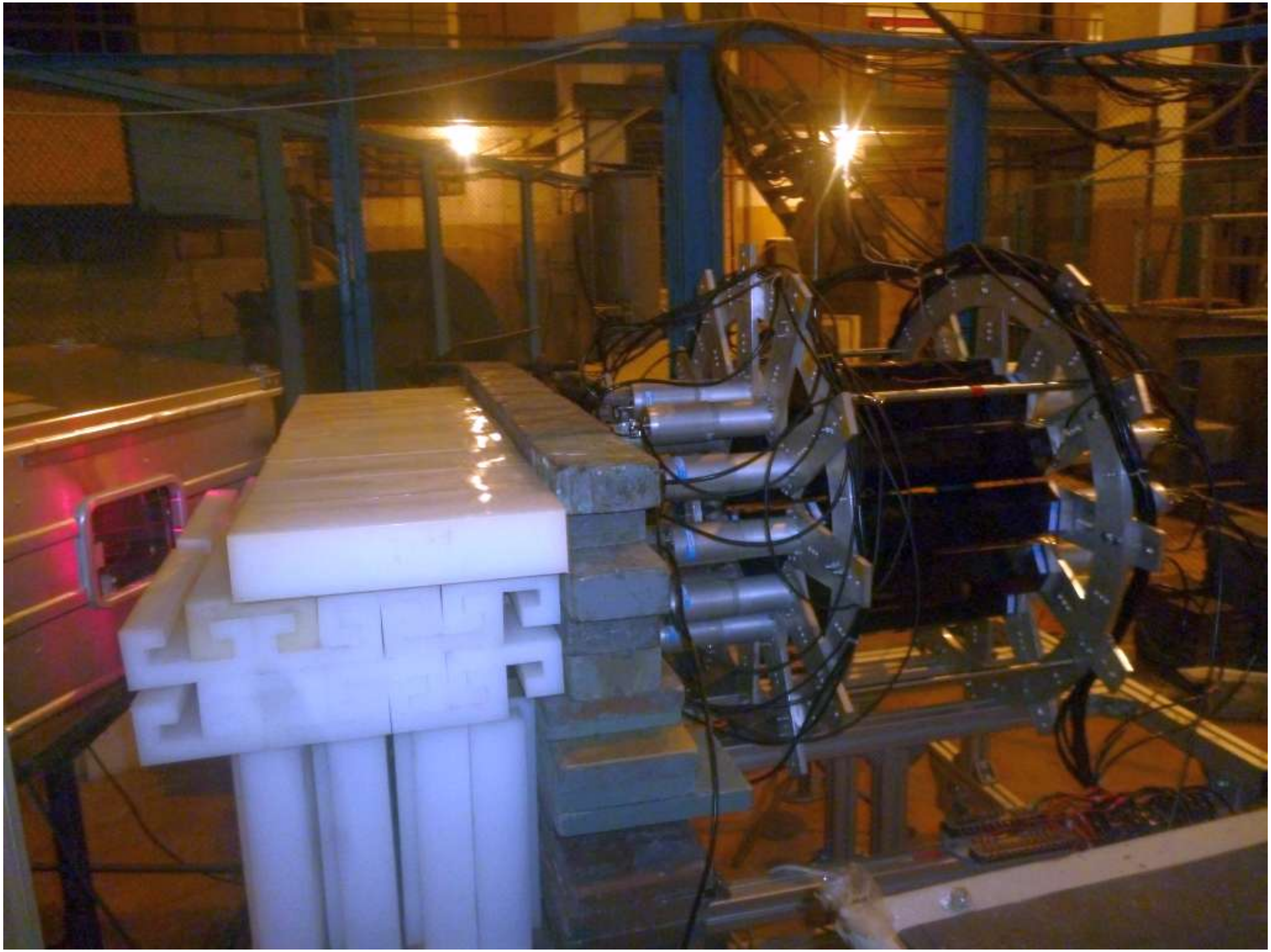


<u>Aim:</u> ***Determination of the angular correlation between the directions of emission of the neutron and the gamma rays emitted from the de-excitation of ^{12}C***

Conservative estimates of the counting rate of detectors in coincidence n-γ-α with available equipment give ~ 100 events per hour.

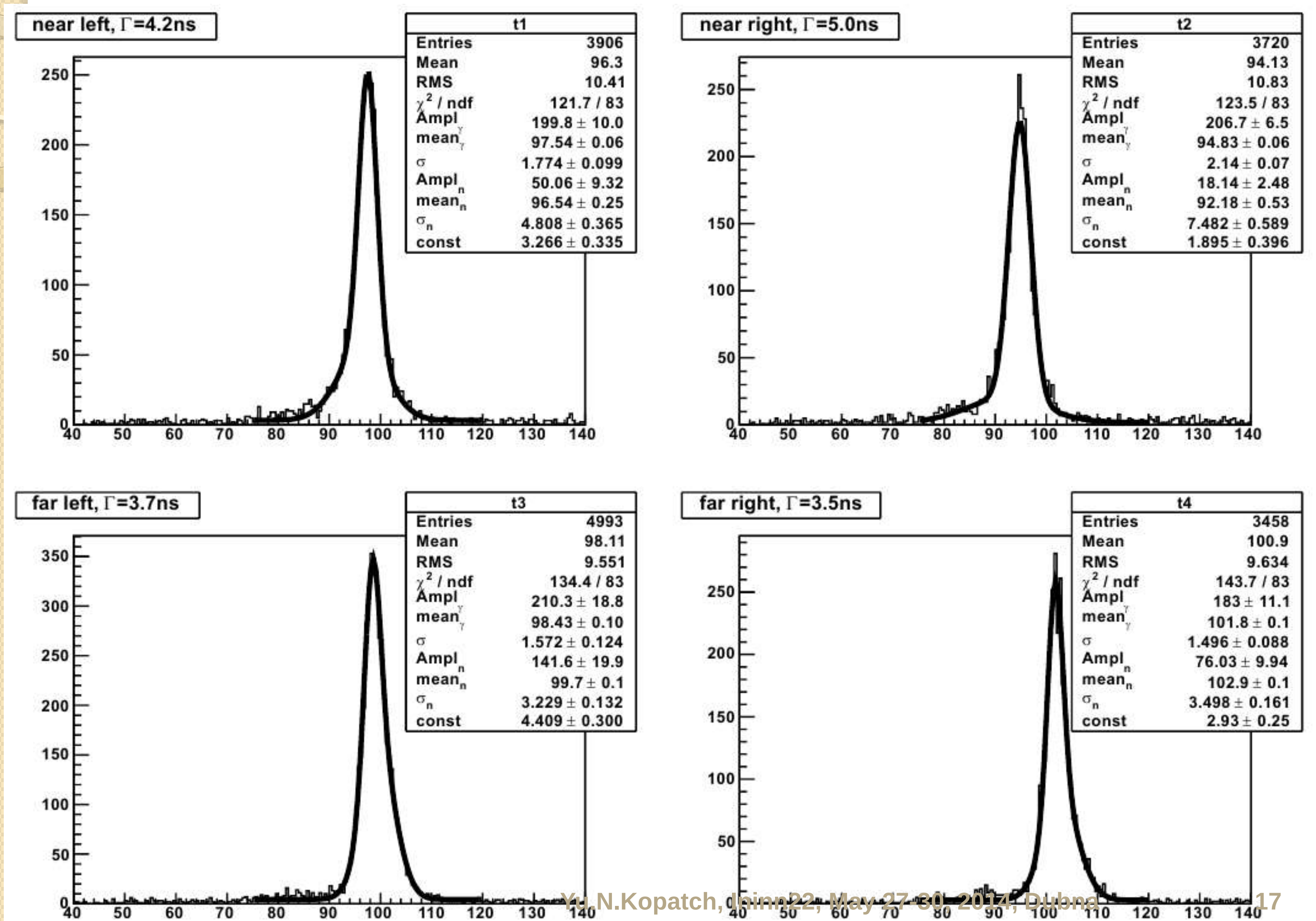
In an experiment conducted earlier, the rate of collection of statistics was ~ 8 (n-γ-α) - events per day

First tests with ING-27 and “Romashka” detector system

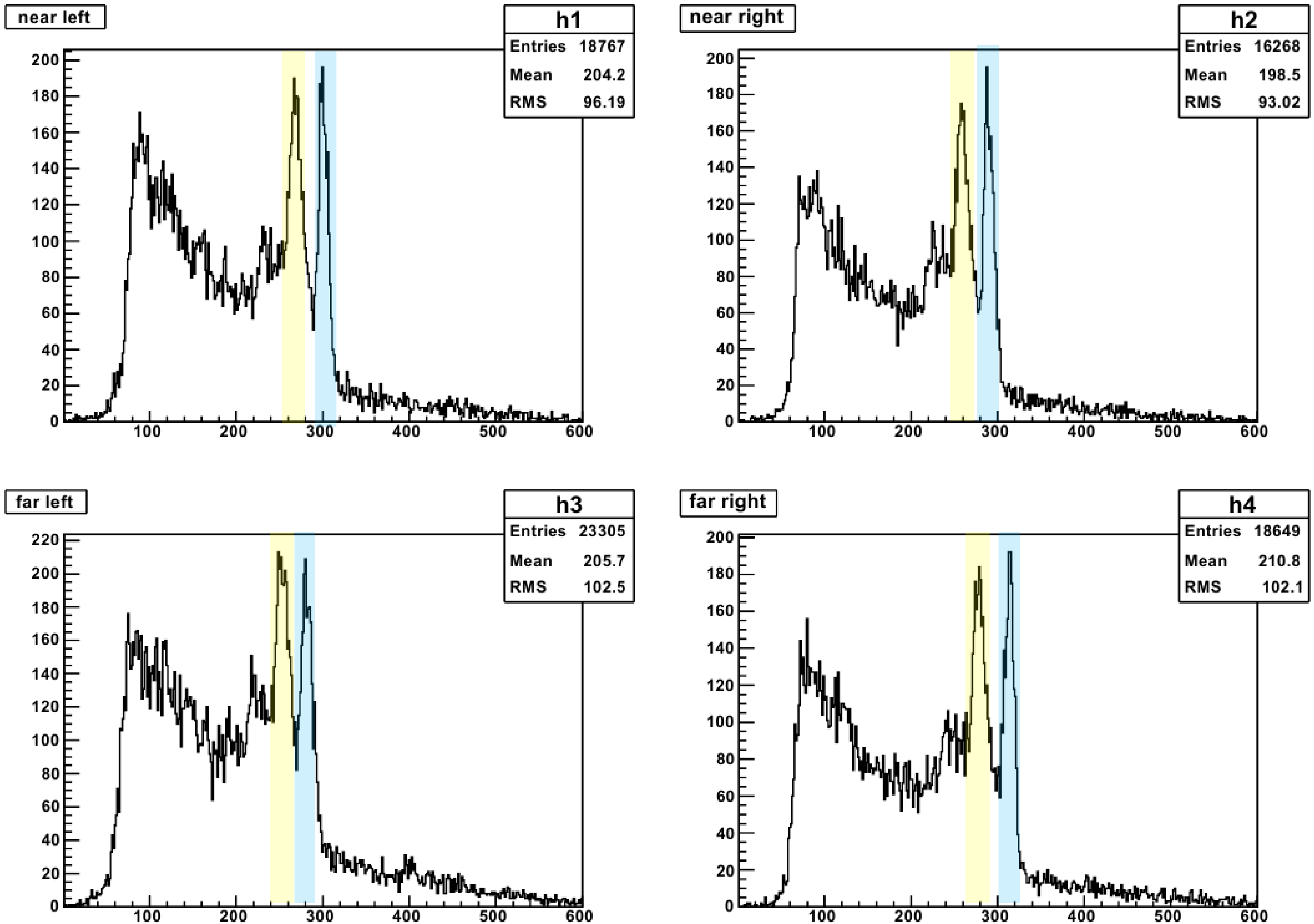


First tests with ING-27 and “Romashka” detector system

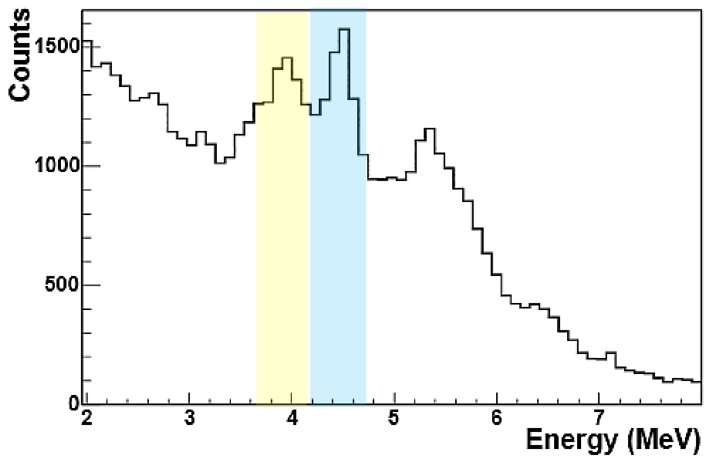
Time spectra from NaI, target – 12C

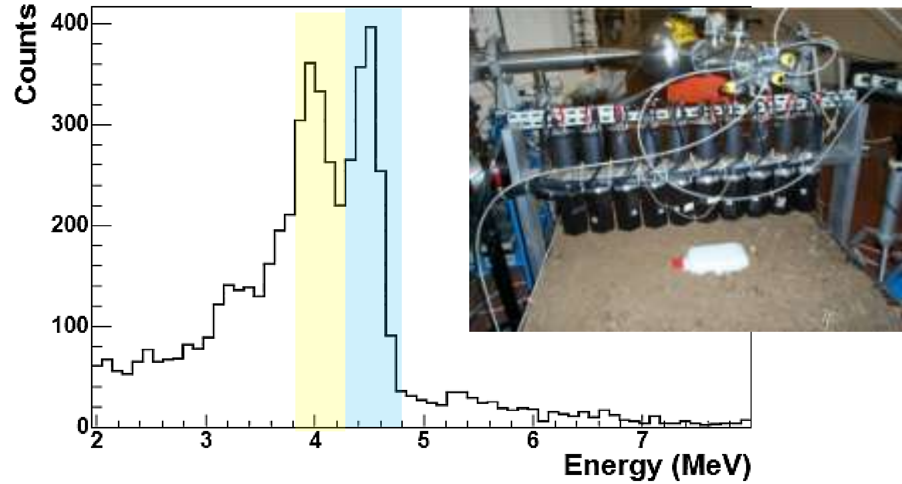


Energy spectra from NaI, target – ^{12}C, in coincidence with the central Si pixel



Comparison with some literature data: S. Pesente, Development of Inspection Systems using 14 MeV Tagged Neutron Beams

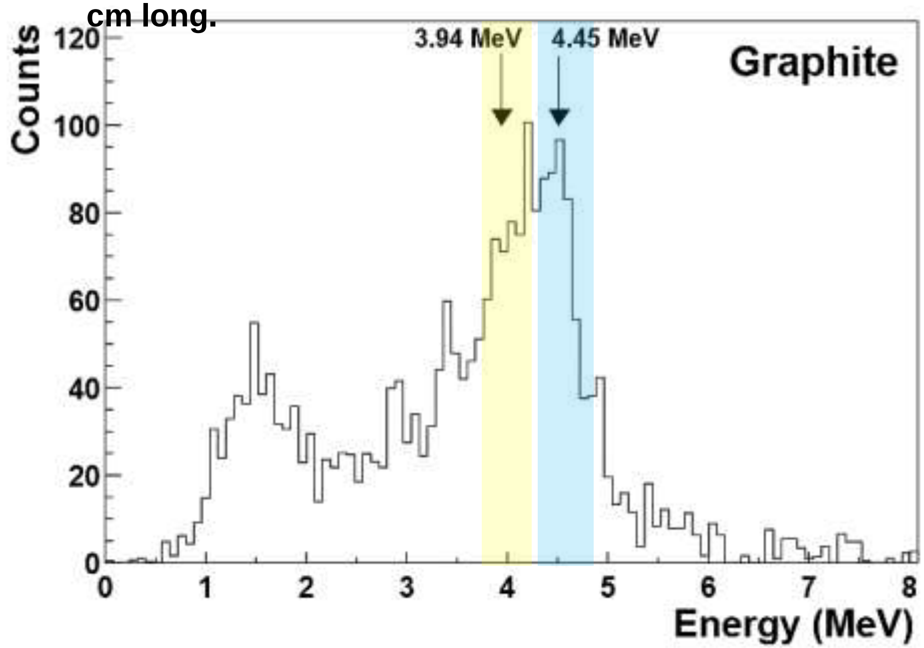




Energy of -rays used for the calibration of the BaF2 detectors

Energy (MeV)	source
1.173	^{60}Co
1.274	^{22}Na
1.332	^{60}Co
2.23	P(n, n'γ)P *full energy*
3.85	O(n, n'γ)O *full energy*
3.94	C(n, n'γ)C *first escape*
4.45	C(n, n'γ)C *full energy*
5.97	O(n, n'γ)O *first escape*
6.13	O(n, n'γ)O *full energy*

10 BaF2 detectors, with hexagonal base (50 cm2)) and 12 cm long.



Comparison with some literature data:

Scintillator	PMT	Timing γ-γ in ^{60}Co (ns)	Timing γ-n in ^{12}C (ns)	FWHM @ 662 keV (%)	FWHM @ 4.44 MeV (%)
Amcrys-H – NaI(Tl) 3"×3"	XP4312B	0.89 ± 0.08	1.14 ± 0.03	7.30 ± 0.10	4.24 ± 0.07
Scionix Holland BV – BGO 3"×3"	XP4312B	1.91 ± 0.05	1.90 ± 0.05	13.35 ± 0.09	6.20 ± 0.06
Amcrys-H – NaI(Tl) 5"×5"	XP4512B	1.44 ± 0.04	1.61 ± 0.05	8.00 ± 0.08	4.87 ± 0.03
Saint-Gobain – NaI(Tl) 5"×5"	XP4512B	1.02 ± 0.09	1.80 ± 0.04	6.92 ± 0.09	3.86 ± 0.06
Cyberstar – BGO 5"×5"	R877	6.68 ± 0.17	5.59 ± 0.14	11.32 ± 0.07	5.14 ± 0.08
Saint-Gobain – NaI(Tl) 5"×5"×10"	XP4512B	1.48 ± 0.03	2.13 ± 0.04	7.39 ± 0.06	4.62 ± 0.05

http://www-ist.cea.fr/publicea/exl-doc/200500001581.pdf

The EURITRACK project: development of a tagged neutron inspection system for cargo containers.

ERITR@C

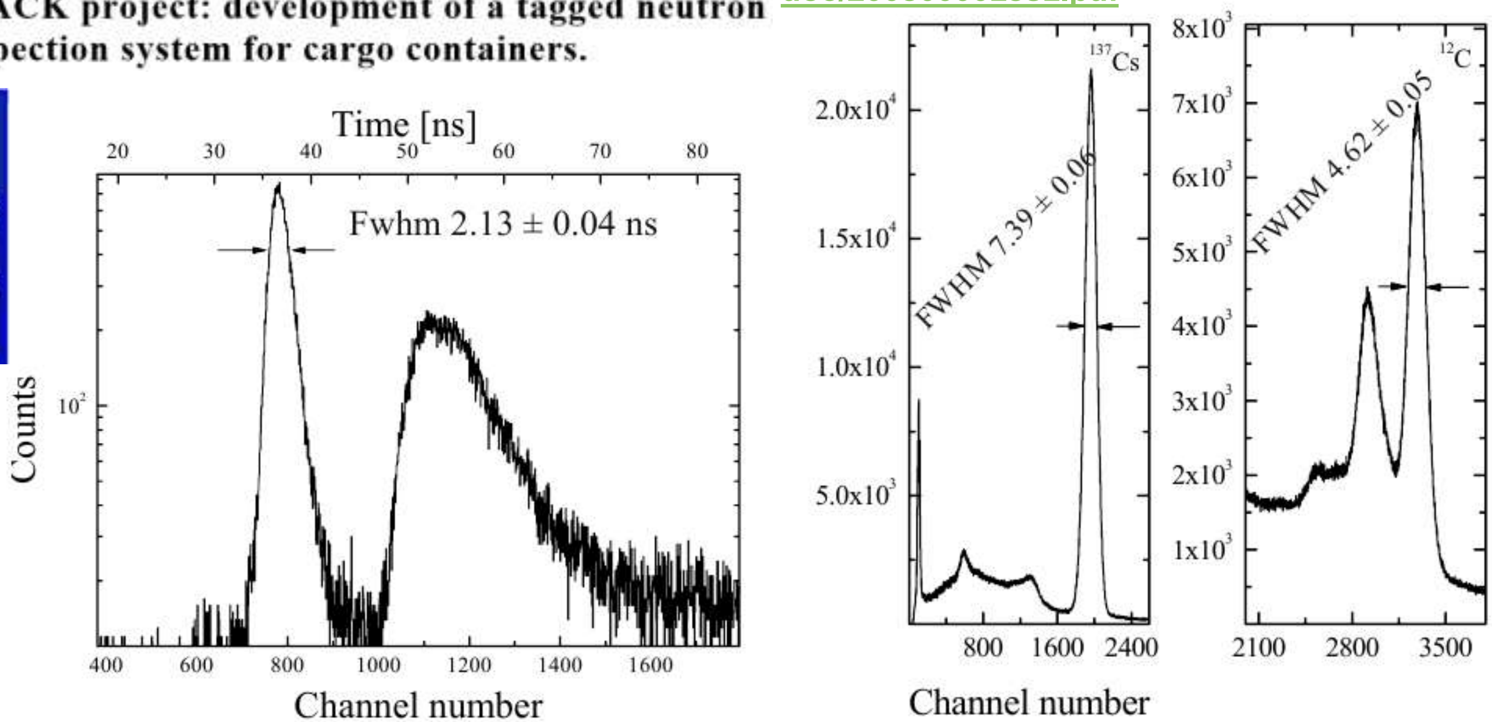
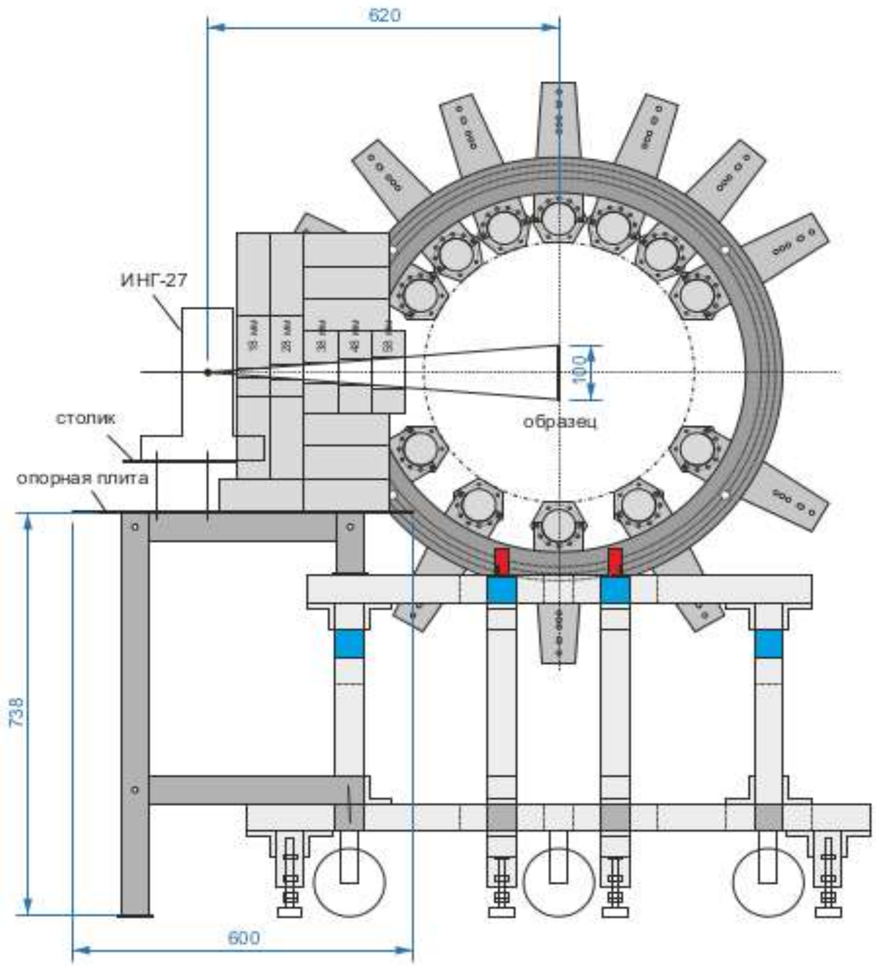


Figure 11. Measured time (left) and pulse-height (right) spectra of the 5"×5"×10" sodium iodide detector.

Design of a detector shielding from the direct neutron beam

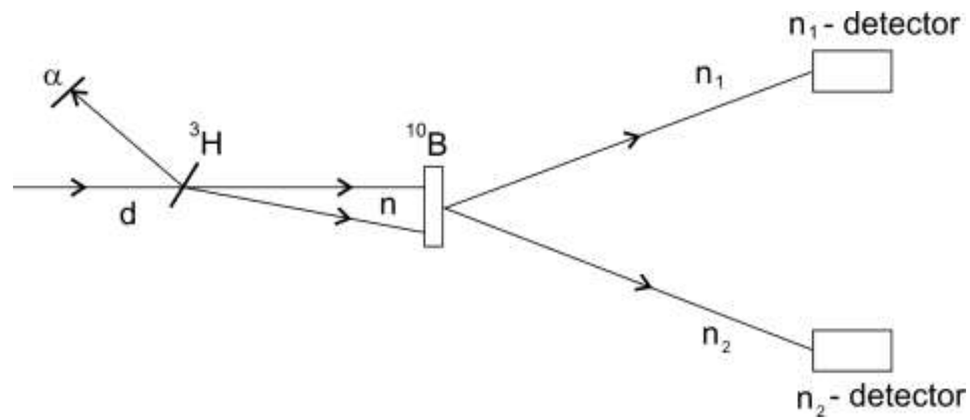


The optimal combination of available shielding materials:

30cm Fe + 10cm BPE + 10cm Pb

Experimental program: basic research

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



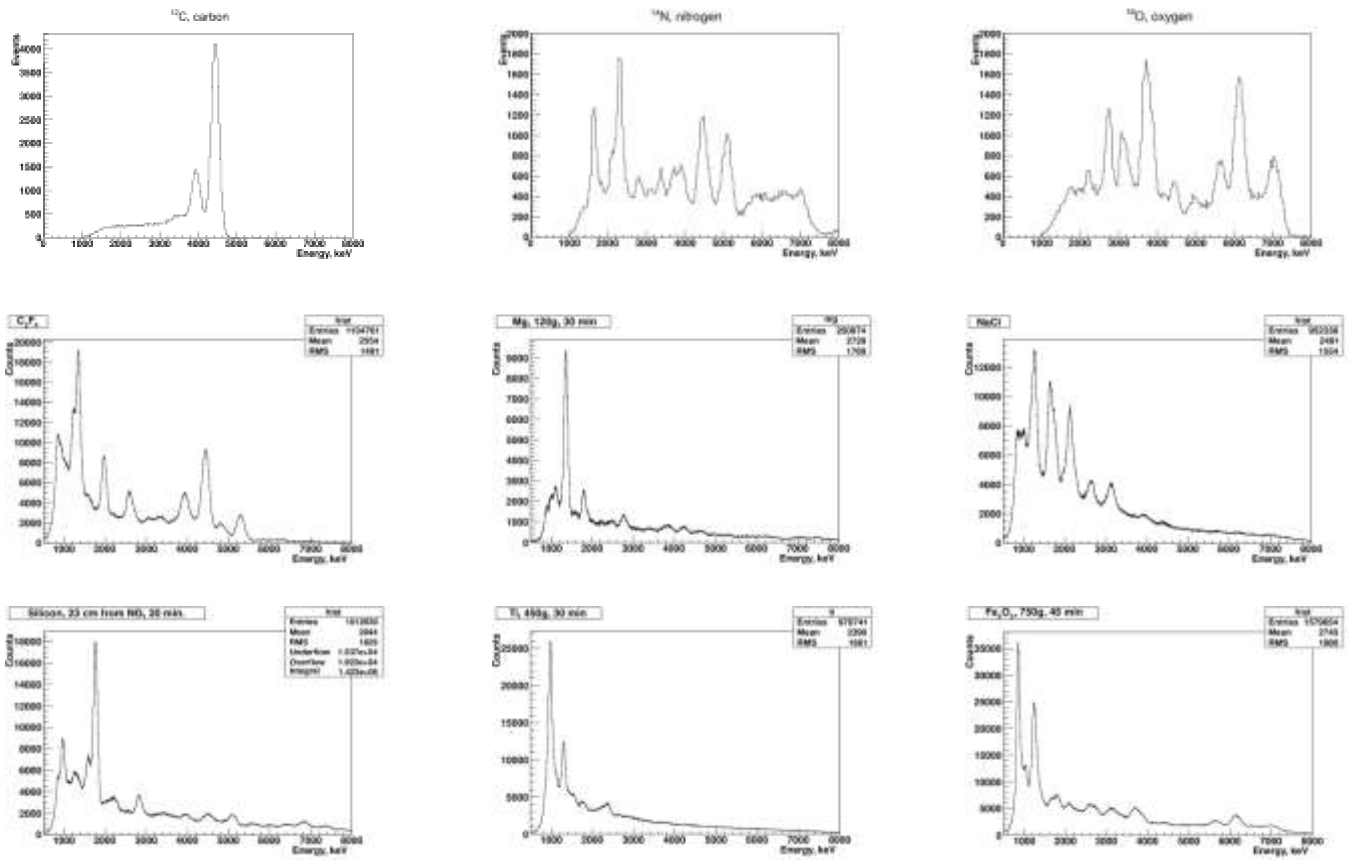
Investigation of the reaction $^{10}B(n,2n)^{9}B \rightarrow p + {}^{8}Be$.

Aim: ***Obtaining information about the low-lying levels of the unstable nucleus*** ^{9}B

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

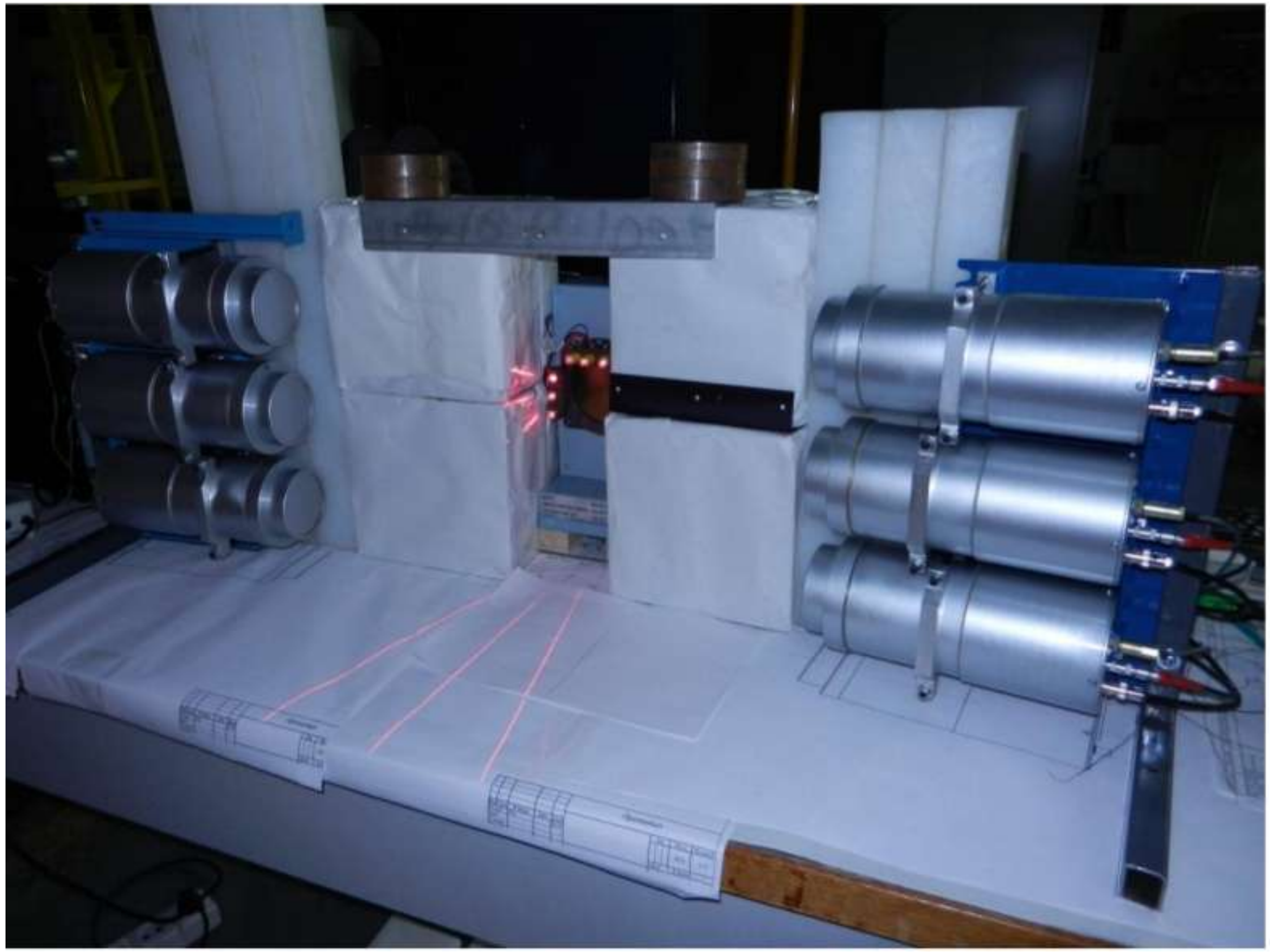
Experimental program: applied research

3. ***Measurement of characteristic gamma - spectra for different elements. Creating a database for identification of complex substances. Development of a technique for non-destructive analysis by TNM.***



The spectra of the characteristic gamma - radiation produced by irradiating by the tagged neutrons of the samples: carbon, nitrogen, oxygen, teflon, magnesium, salt, silicon, titanium, iron oxide (from left to right, top to bottom).

Example: non-destructive analysis of kimberlite ores, search for diamonds



Experimental stand:

- **neutron generator with 64-pixel α-detector**
- **6 BGO γ-detectors**

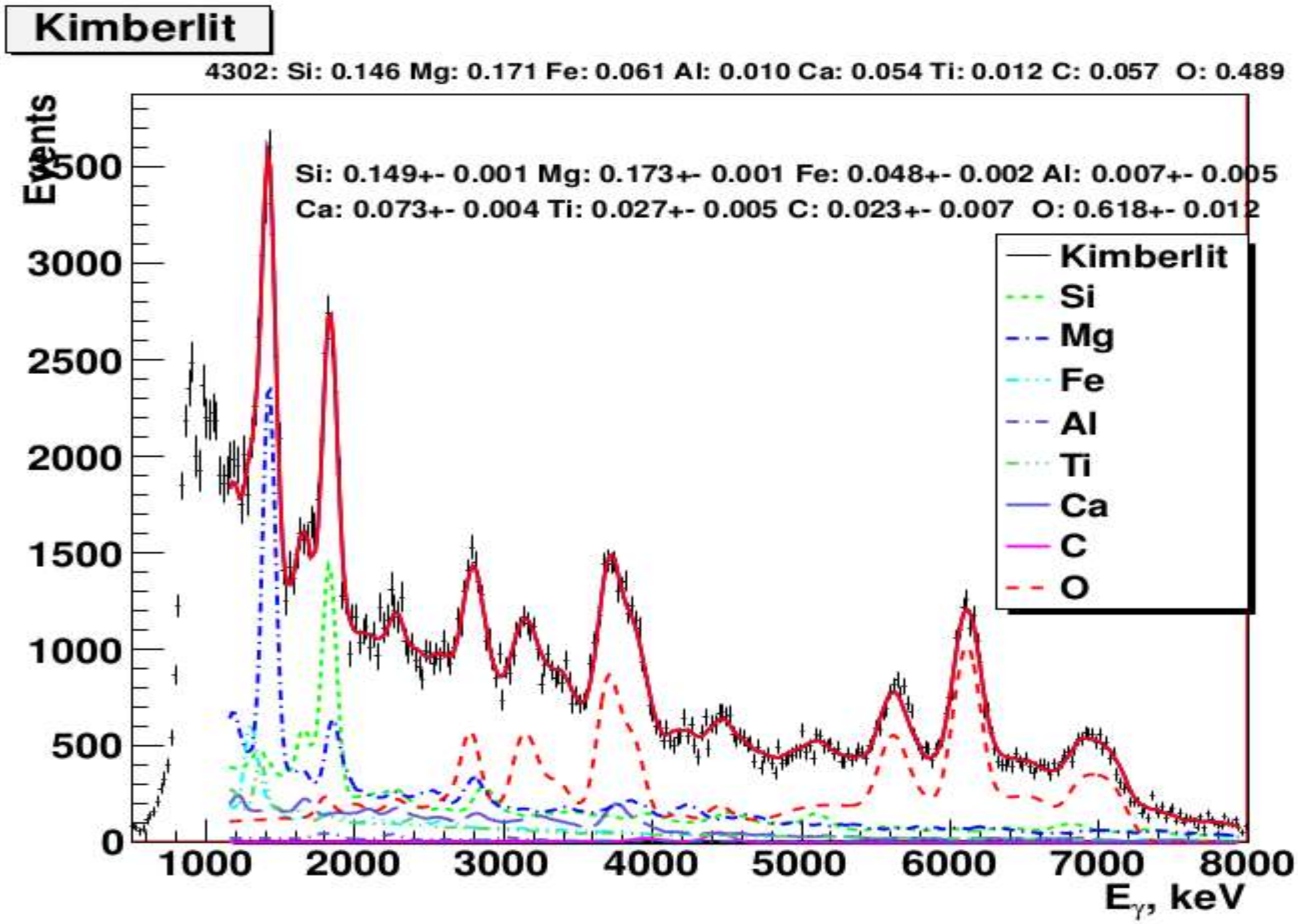
Example: non-destructive analysis of kimberlite ores – search for diamonds

A typical 64-pixel spectrum obtained by irradiating a sample of kimberlite

The condition for finding the diamond is a local excess of the count rate for gamma-rays with energies ~4.43 MeV (characteristic line of carbon)

One of the samples showed the excess of the local carbon content above the average ranging from 3.3 to 5.8 σ, depending on the angle at which the sample was irradiated.

Example: non-destructive analysis of kimberlite ores – determination of the element composition

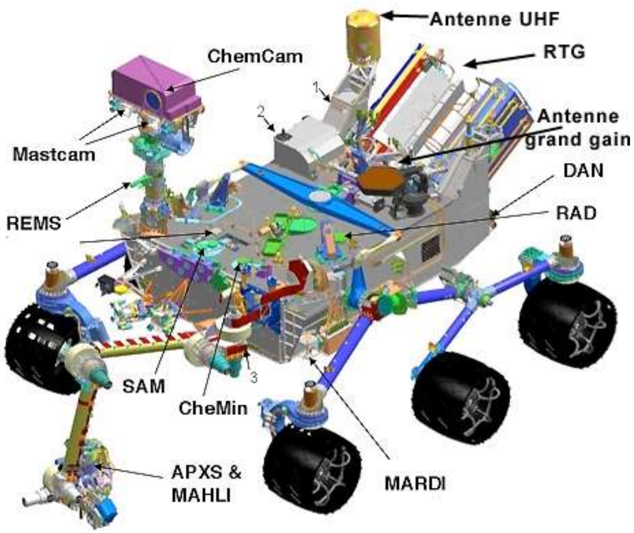


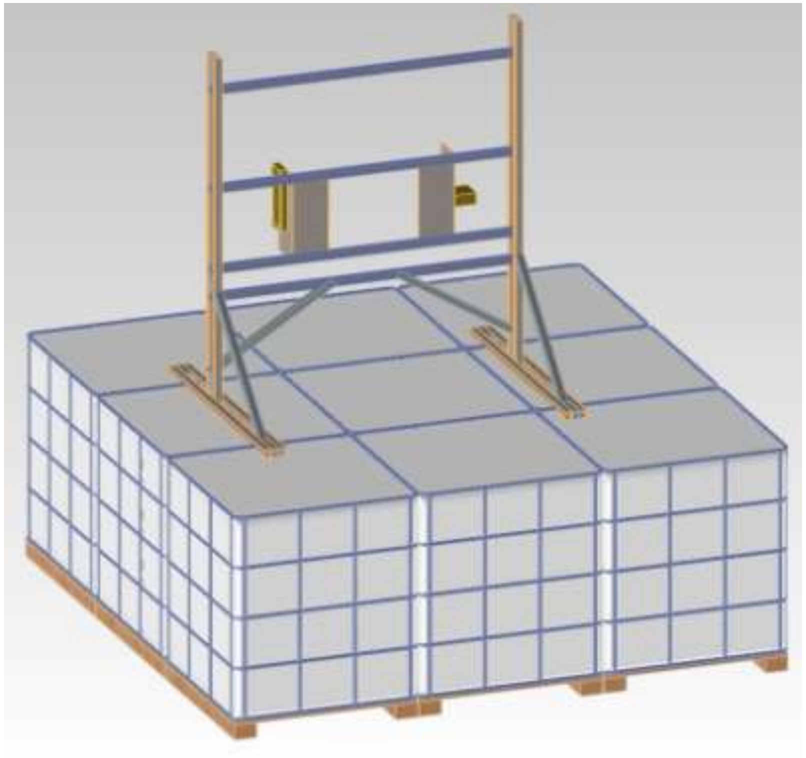
Decomposition of the total gamma-ray spectrum for a kimberlite sample into elementary components. The element contents, determined by the chemical methods, are shown above the figure.

Experimental program: applied research

4. Development and study of the model of the Martian soil

Curiosity





<u>Aim:</u> ***Determination of the absolute concentration of the chemical elements that make up the Martian surface. The determination is performed by the analysis of gamma-ray line intensities, which in turn depend on the spectral density of the neutron flux interacting with the nuclei of the major rock-forming elements.***

Main works and stages in the framework of the project

№	Name of main works and stages	Work periods (year, quarter)	
		Beginning	End
1	Conduction of test measurements with the neutron generator and detection system “Romashka” to determine the parameters and structure of the shielding	2013, IV	2014, I
2	Development of the combined shielding for gamma-radiation and neutron detectors	2014, I	2014, II
3	Conduction of measurements of characteristic gamma-spectra for various elements. Creation of data base for element identification.	2014, II	2016, IV
4	Conduction of experiments on measurements of angular correlations of gamma-ray emission in the reactions of neutron inelastic scattering on light nuclei.	2014, IV	2016, IV
5	Conduction of experiments on measurement of cross-sections in the (n,2n), (n,n`) reactions.	2015, I	2016, IV
6	Studies of the Martian soil model.	2015, I	2016, IV
7	Development of the technique for studies of the elemental composition of soils and minerals.	2014, I	2016, IV

Summary

- The project aimed at the experimental investigations in the field of basic and applied nuclear physics using tagged neutron beam is proposed with participation of 4 JINR laboratories and 4 external institutes.

- The major equipment needed for the project is already available.

- First measurements with the tagged neutron beam and gamma-ray and neutron detectors have been performed and give promising results.

- We believe that good experience of the teams participating in the project assures successful realization of its scientific program.

Thank you
for your attention