Applications of the Tagged Neutron Method for Fundamental and Applied Research

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Project TANGRA @ JINR: TAgged Neutrons and Gamma RAys

Development of the tagged neutron method for determining the elemental structure of matter and nuclear reactions research

Main participants:

- *JINR (FLNP, VBLHEP, DLNP, LRB), Dubna, Russia*
- *N.L. Dukhov All-Russian Automation Research Institute, Moscow, Russia.*
- *Lomonosov Moscow State University, Moscow, Russia.*
- *Institute Ruđer Bošković, Zagreb, Croatia*
- *INRNE, Bulgarian Academy of Sciences, Sofia, Bulgaria*
- *BHU Varanasi, India*
- *LLC DIAMANT, Dubna, Russia*

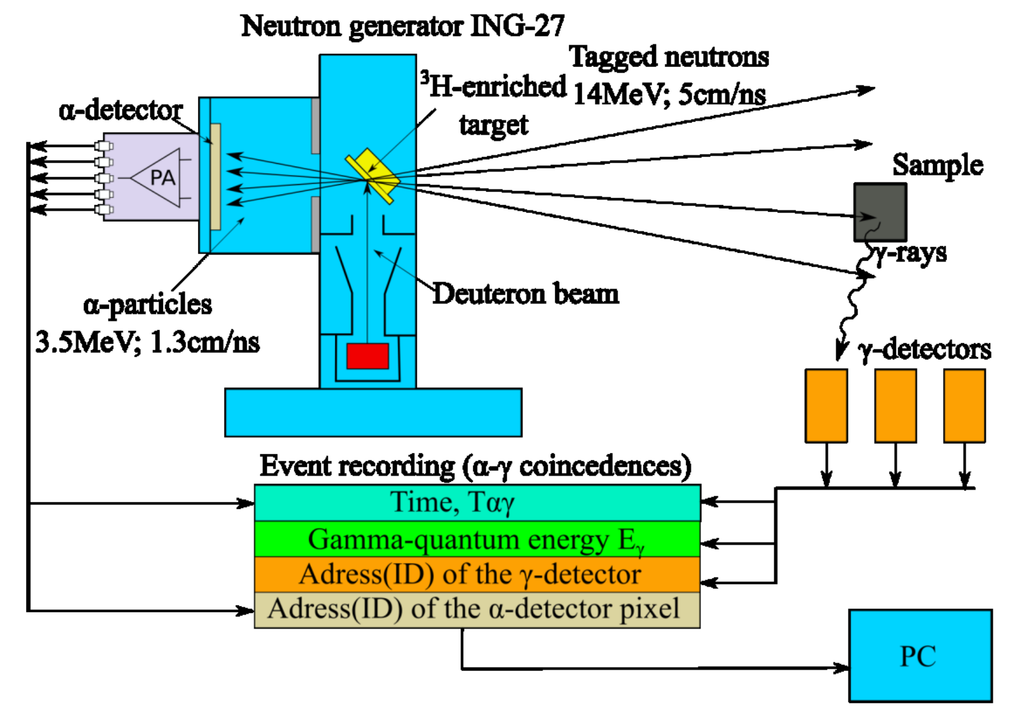
The Tagged Neutron Method (TNM) or Associated Particle Technique

$D + T \rightarrow {}^4He$ (3.5MeV) + n (14.1MeV)

The 14.1 MeV neutron is tagged in time and direction by detecting the associated α-particle released in the opposite direction.

Main advantages of the method:

- significantly reduced background
- direct measurement of the neutron flux
- position sensitivity
- possibility to select time-correlated events using coincidences



Neutron generators

Some characteristics of commercial neutron generators

Type of NG	Metherial of α-detecor	Number of tagged beams	Pixel size (mm)	Distance between pixels (mm)
Sodern, Euritrack	Si	64	5.8	0.2
API-120	YAP	256	3	-
ING-27	Si	9	10	1
ING-27-64	Si	64	6	1
ING-27-256	AsGa	256	4	0,1

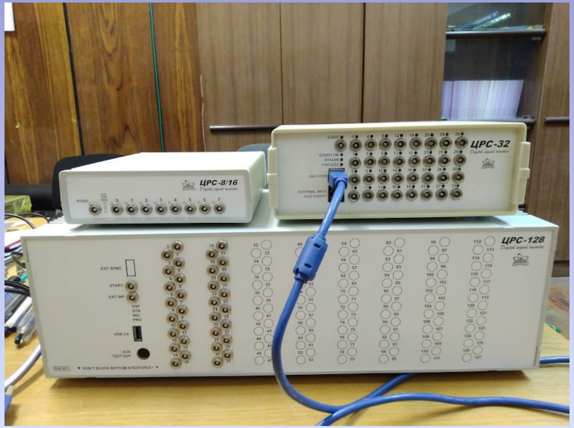
Produced by

N.L. Dukhov All-Russian Automation Research Institute

Main characteristics:

Maximal intensity	~$5 \cdot 10^7$ c^{-1}
Neutron energy	14.1 MэВ
Neutron radiation mode	steady-state
Operation time	~800 hours

Electronics and data acquisition system

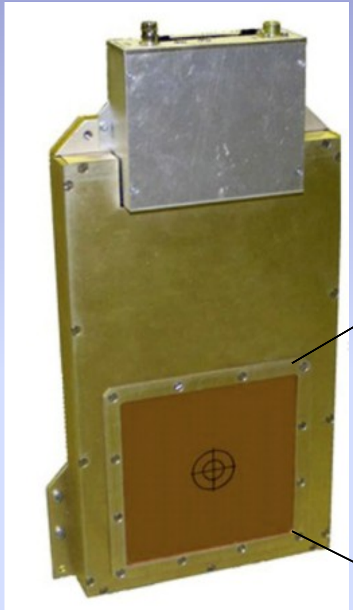


Digitizers ADCM-32/64

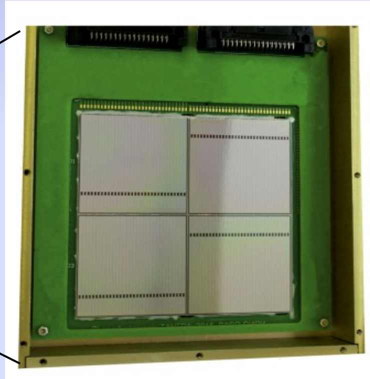
Digitizers DSR-2/8/32/128

Parameters	***ADCM***	***DSR***
Number of channels	*16 / 32 / 64*	*2 / 8/ 32 / 128*
ADC resolution	*14 bits*	*11/16 bits*
Sampling frequency (MHz)	*100 / 66*	*200 / 100*
Interface	*PCI-e*	*USB-3*
Data analysis type	*PC*	*FPGA*
Maximal event rate per channel	*~10^5 evt/sec*	*~5×10^6 evt/sec*

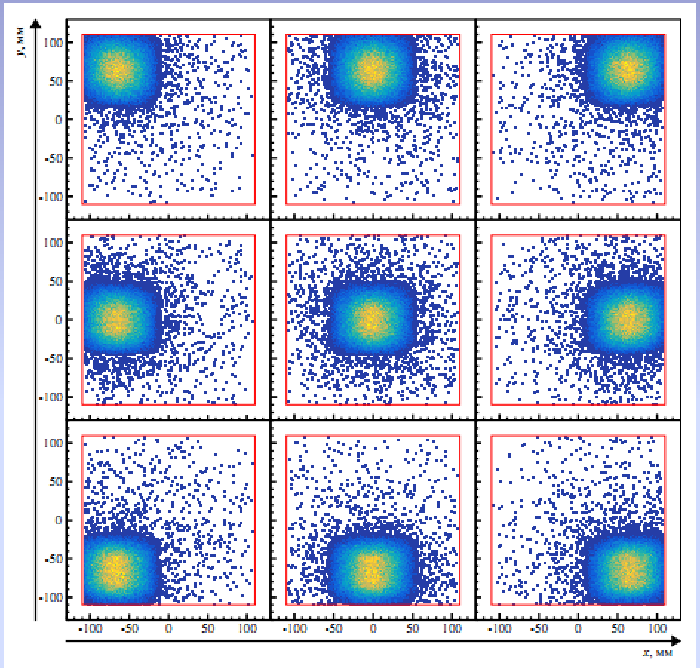
Measurements of tagged neutron beams profiles



- 120x120 mm sensitive area
- 300 μm thickness
- 2 mm resolution

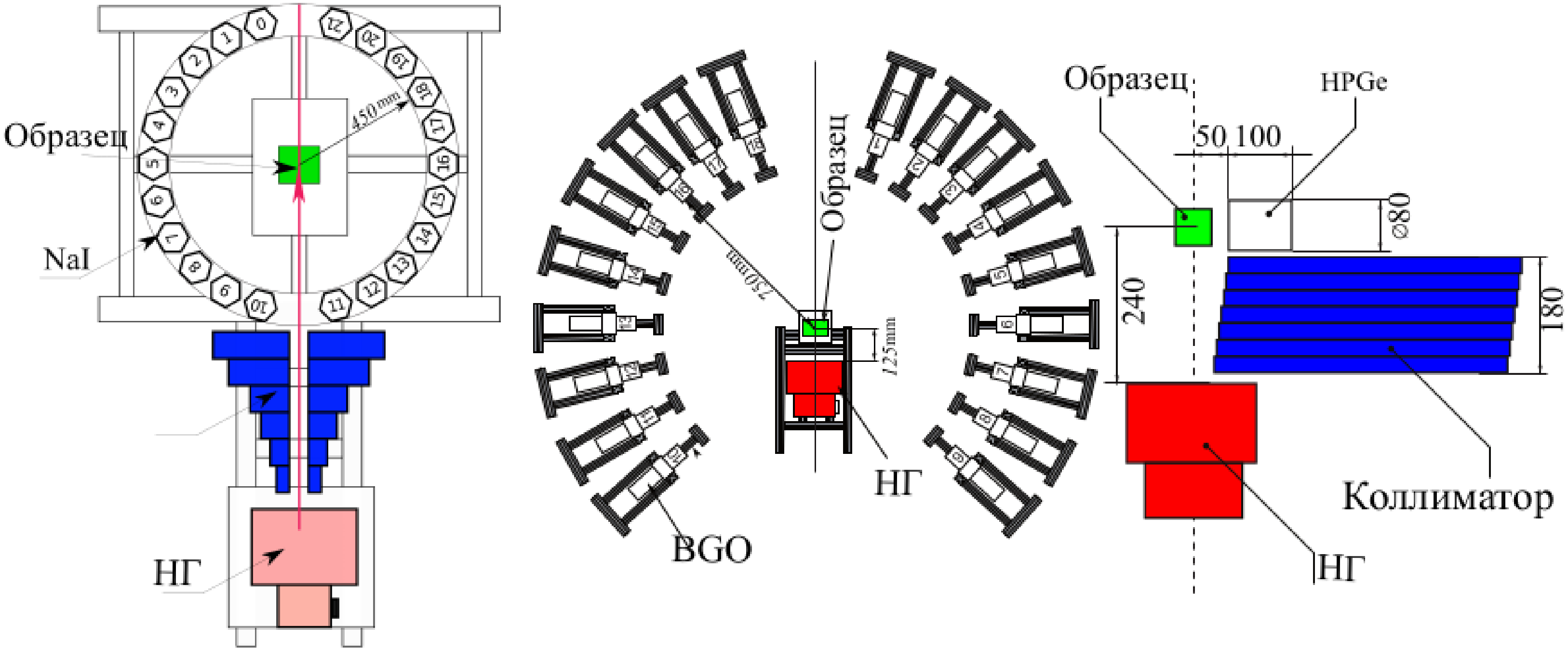


2-coordinate position sensitive silicon detector



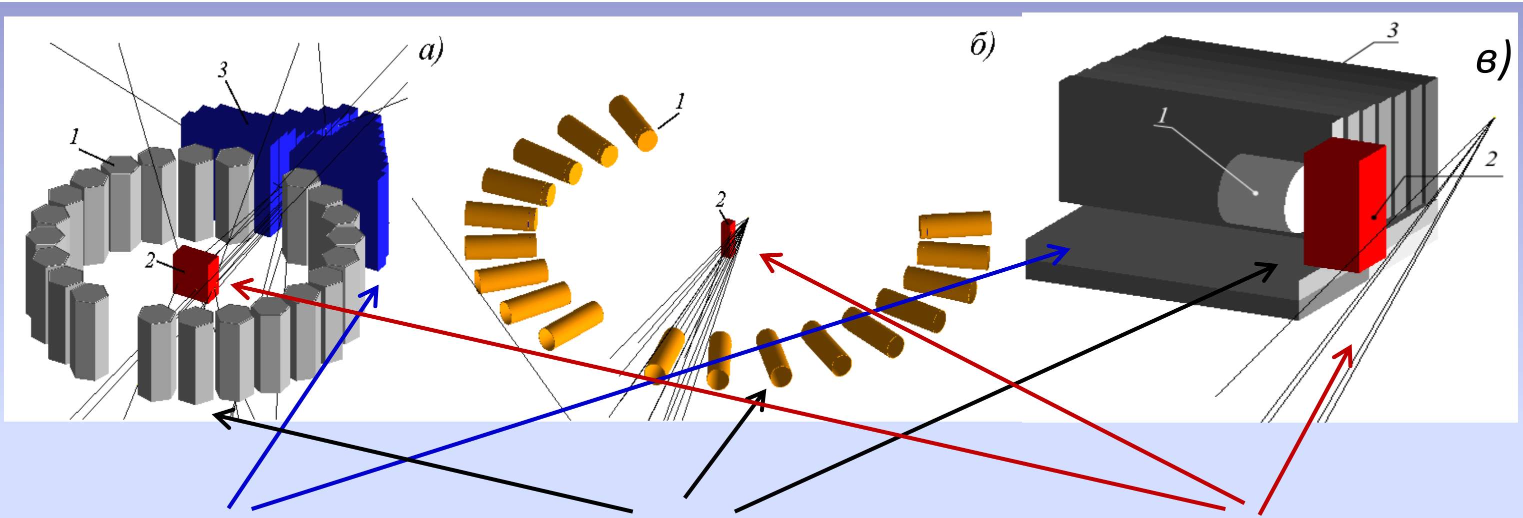
Beam profiles from the 9-pixel ING-27

Experimental setup configurations



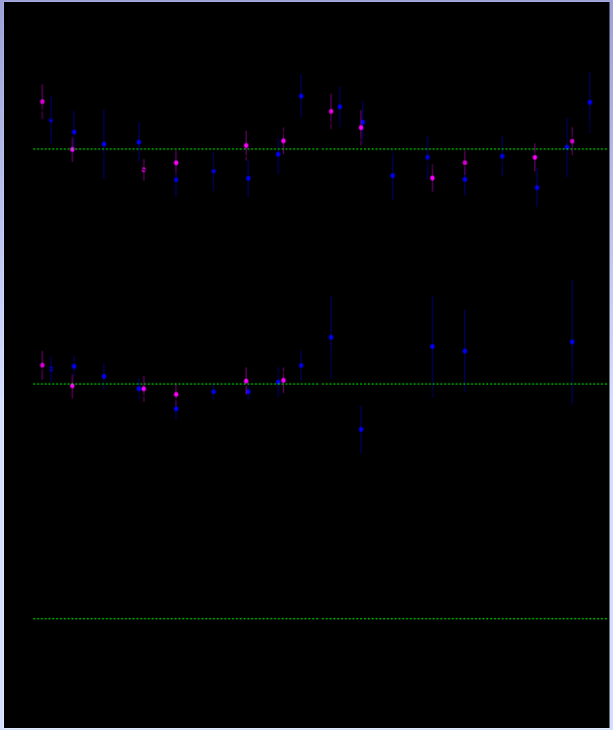
22 NaI(Tl) detectors **18 BGO detectors** **1 HPGe detector**

Monte Carlo simulation



- **Optimization of the experimental geometry**
- **Determination of the detector solid angles and geometric corrections**
- **Determination of corrections for multiple neutron scattering and self-absorption of gamma-rays in the sample.**

Angular distributions of gamma-rays from inelastic scattering of 14.1 MeV neutrons



Angular distributions of γ-rays for chromium

Angular distributions of γ-rays are the normalized differential cross sections:

$$\frac{d\sigma}{d\Omega}(\Theta) = \frac{\sigma^{\gamma}}{4\pi} W(\theta)$$

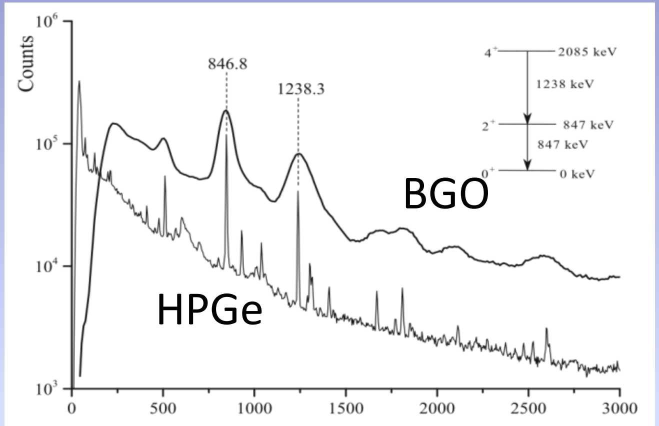
$$W(\theta) = 1 + \sum_{l=2,4\ldots}^{2J} a_l P_l(\cos\theta)$$

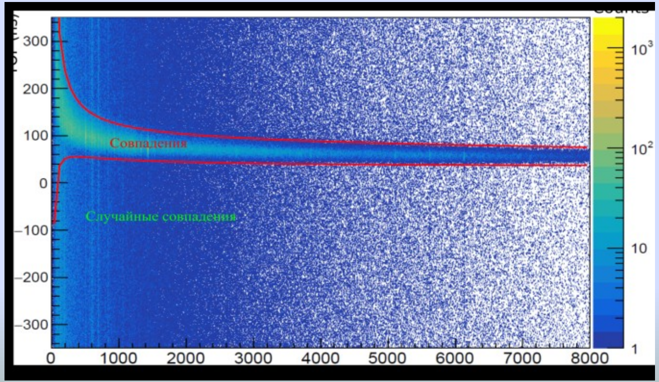
Eγ (keV)	Ref.	a_2	a_4
935.5	**Our work**	**0.34 ± 0.02**	*
	Abbodanno1973	0.35 ± 0.09	*
	Oblozinsky1992	0.27 ± 0.06	*
1333.6	**Our work**	**0.23 ± 0.02**	*
	Abbodanno1973	0.41 ± 0.09	*
	Oblozinsky1992	0.30 ± 0.05	*
1434.1	**Our work**	**0.16 ± 0.01**	**-0.06 ± 0.02**
	Abbodanno1973	0.18 ± 0.05	-0.06 ± 0.07
	Oblozinsky1992	0.13 ± 0.03	0.03± 0.04
1530.7	Oblozinsky1992	-0.12 ± 0.31	*
	Our work	**0.14 ± 0.05**	*
2038.2	**Our work**	**0.15 ± 0.04**	*
3128.9	**Our work**	**0.01 ± 0.03**	

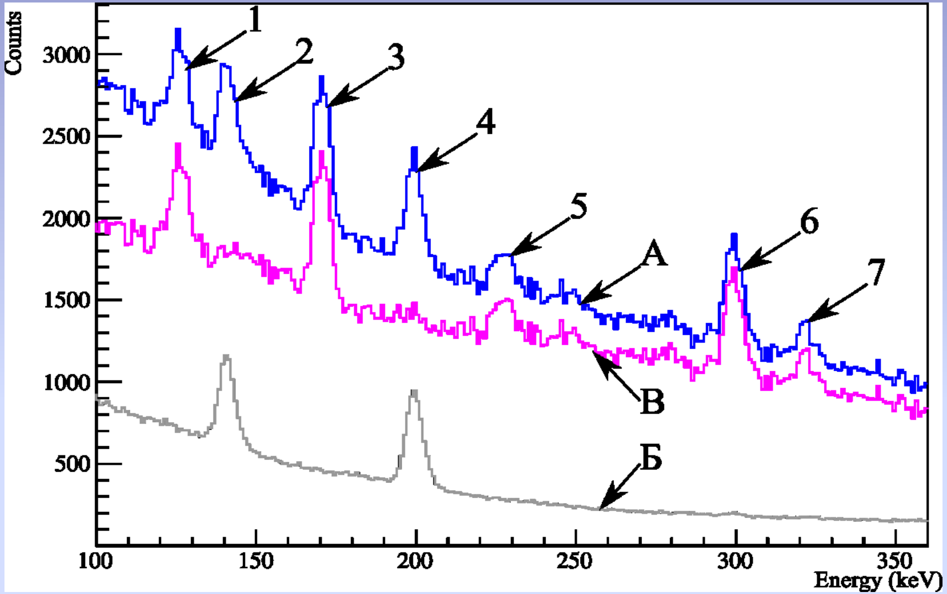
Table of gamma-ray yields for chromium

E_γ (keV)	Reaction	J_i^P (E_i, keV)	J_j^P (E_j, keV)	Y_γ, %		
				Our work	[42]	[3]
124,4	$^{52}Cr(n,p)^{52}V$	(141,6)	(17,2)	2,4 (0,5)		
226,3	$^{50}Cr(n,p)^{50}V$	(226,2)	(0)	3,0 (0,6)		
320,1	$^{52}Cr(n,d)^{51}V$	(320,1)	(0)	2,2 (0,8)		1,8 (0,1)
567,0	$^{52}Cr(n,n')^{52}Cr$	(4039,2)	(3472,2)	5,0 (0,9)		
600,2	$^{52}Cr(n,n')^{52}Cr$	(4015,5)	(3415,3)	10,0 (1,6)		
645,7* 647,5*	$^{52}Cr(n,p)^{52}V$ $^{52}Cr(n,n')^{52}Cr$	(793,5) (3415,3)	(147,8) (2767,8)	8,5 (1,0)		8,9 (0,3)
704,5	$^{52}Cr(n,n')^{52}Cr$	(3472,2)	(2767,8)	-		5,4 (0,2)
744,2* 749,1*	$^{52}Cr(n,n')^{52}Cr$ $^{52}Cr(n,2n)^{51}Cr$	(3113,9) (749,1)	(2369,6) (0)	12,3 (1,5)	16,3 (2,9)	9,1 (0,3) 5,4 (0,2)
783,3	$^{50}Cr(n,n')^{50}Cr$	(783,3)	(0)	4,2 (0,5)		
791,3	$^{52}Cr(n,2n)^{51}Cr$	(4563,0)	(3771,7)	2,9 (0,5)		
834,9	$^{54}Cr(n,n')^{54}Cr$	(834,9)	(0)	3,1 (0,4)		
848,2	$^{52}Cr(n,n')^{52}Cr$	(3615,9)	(2767,8)	7,3 (0,5)		
935,5	**$^{52}Cr(n,n')^{52}Cr$**	**(2369,6)**	**(1434,1)**	**33,5 (0,8)**	**26,9 (3,8)**	**30,3 (1,2)**
1164,6	$^{52}Cr(n,2n)^{51}Cr$	(1164,6)	(0)	-		4,6 (0,2)
1246,3* 1247,7*	$^{52}Cr(n,n')^{52}Cr$	(3615,9) (4015,5)	(2369,6) (2767,8)	5,8 (0,9)		5,0 (0,2)
1289,5	$^{53}Cr(n,n')^{53}Cr$	(1289,5)	(0)	3,3 (0,7)		
1333,7	**$^{52}Cr(n,n')^{52}Cr$**	**(2767,8)**	**(1434,1)**	**26,4 (0,8)**	**22,1 (4,0)**	**26,2 (1,0)**
1434,1	**$^{52}Cr(n,n')^{52}Cr$**	**(1434,1)**	**(0)**	**100**	**100**	**100**
1530,7	**$^{52}Cr(n,n')^{52}Cr$**	**(2964,8)**	**(1434,1)**	**6,8 (0,6)**	**9,5 (3,0)**	**5,1 (0,2)**
1727,7* 1730,4*	$^{52}Cr(n,n')^{52}Cr$	(3161,7) (4100,0)	(1434,1) (2369,6)	5,7 (0,7)		3,3 (0,1)
2038,2	**$^{52}Cr(n,n')^{52}Cr$**	**(3472,2)**	**(1434,1)**	**1,7 (0,5)**		
2257,7	$^{52}Cr(n,n')^{52}Cr$	(4627,3)	(2369,6)	1,1 (0,5)		
2337,6	$^{52}Cr(n,n')^{52}Cr$	(3771,7)	(1434,1)	2,1 (0,6)		
3128,9	**$^{52}Cr(n,n')^{52}Cr$**	**(4563,0)**	**(1434,1)**	**2,0 (0,7)**		

TNM with high resolution gamma spectrometry







– energy spectrum in the coincidence window

– random background in the same coincidence window

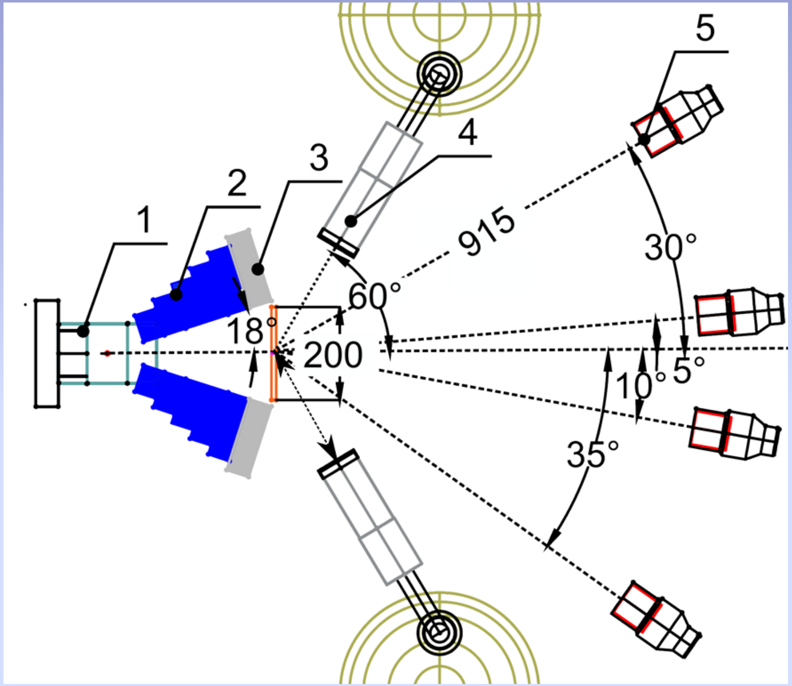
– Pure spectrum after background subraction

New experimental setup

Setup for measuring γ-radiation cross sections. Includes 2 - HPGe and 4 - LaBr detectors. The geometry is optimized using Geant4.

Simultaneous measurement of γ-ray emission cross sections and angular distributions

We plan to measure:
Li, Be, B, C, N, O, F, Na, Mg, Al, Si, P, S,Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu,Zn, Ga, Ge, As, Se, Br, Sr, Y, Zr, Nb, Mo,Pd, Ag, Cd, In, Sn, Sb, Te, I, Ba, Ta, La,Ce, Nd, Hf, W, Hg, Pb, Bi, U



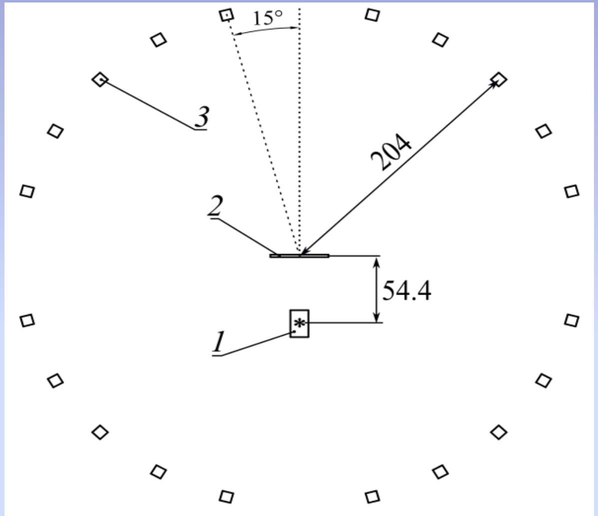
1 – Ing-27; 2 – iron shielding; 3 – lead shielding; 4 – HPGe detectors; 5 – $LaBr_3$ detectors

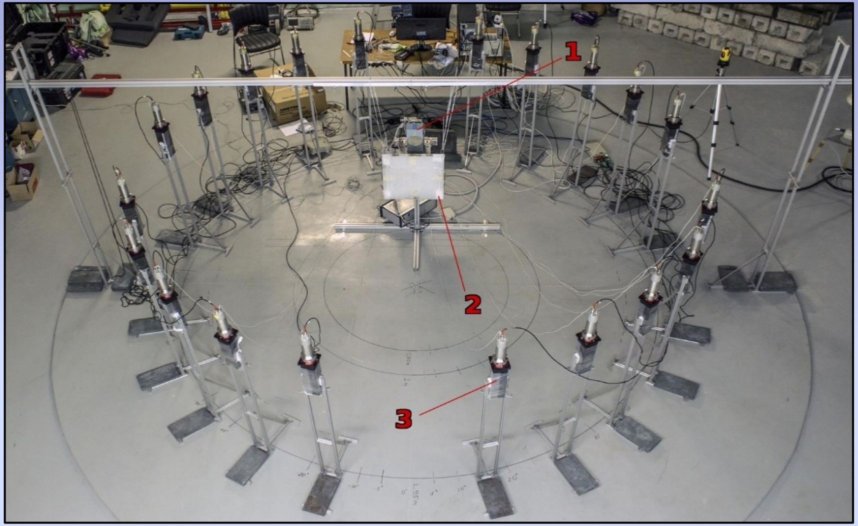
First measurements with standard samples

Results of test measurements of γ-ray cross sections for ^{28}Si, ^{12}C and ^{16}O in comparison with literature data

Eγ (keV)	Reaction	σ (mb)		
		TANGRA	Recommended value	Range of experimental values
1779.0	^{28}Si(n,n’)^{28}Si + ^{29}Si(n,2n’)^{28}Si	350 ± 20	403 ± 20	293 ± 28. . . 488 ± 70
6129.9	^{16}O(n,n’)^{16}O	113 ± 10	148 ± 10	84 ± 17. . . 179 ± 22
4438.9	^{12}C(n,n’)^{12}C	175 ± 6	187 ± 5	121 ± 8. . . 440 ± 80

Measurement of angular distribution of scattered neutrons on 12C

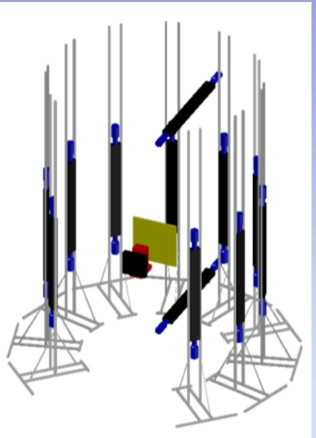


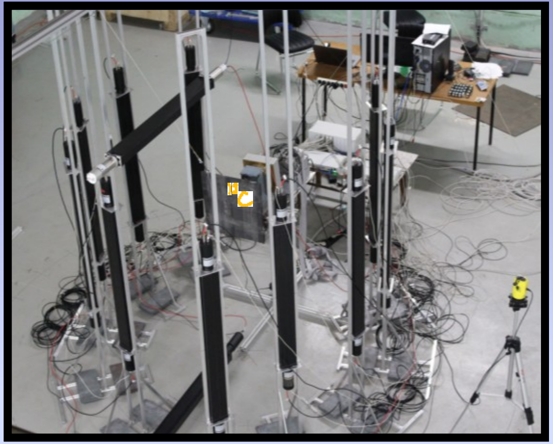


Main aim: to identify excited states of ^{12}C and determine their properties.

See report of D. Grozdanov at ISINN-30

Experimental and theoretical study of (n-n′-γ) correlations

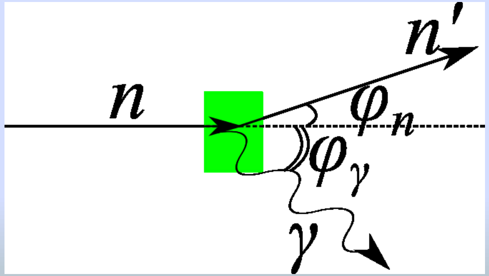


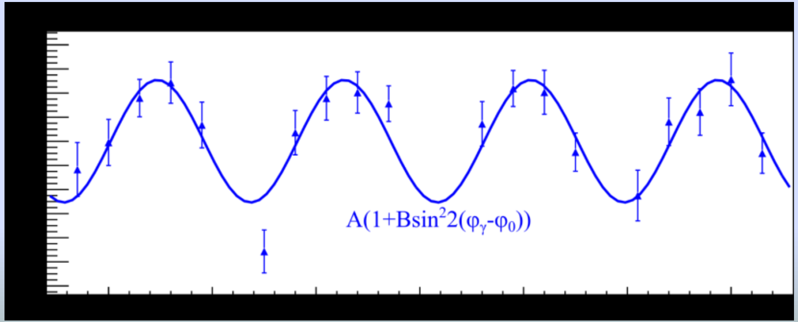


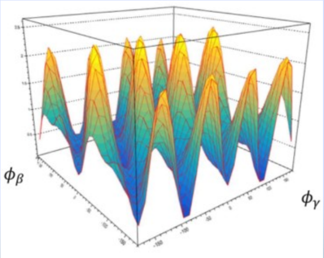
(n′,γ) correlations are important for:

- Understanding the reaction mechanism
- Testing the theoretical predictions
- Checking for nuclear forces invariance for *n* and *p*

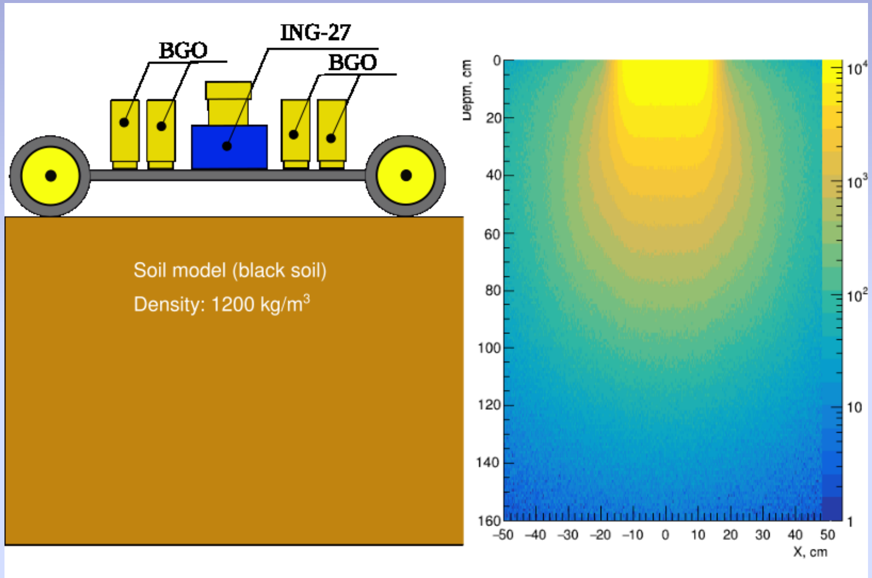
See report of P. Filonchik at ISINN-30



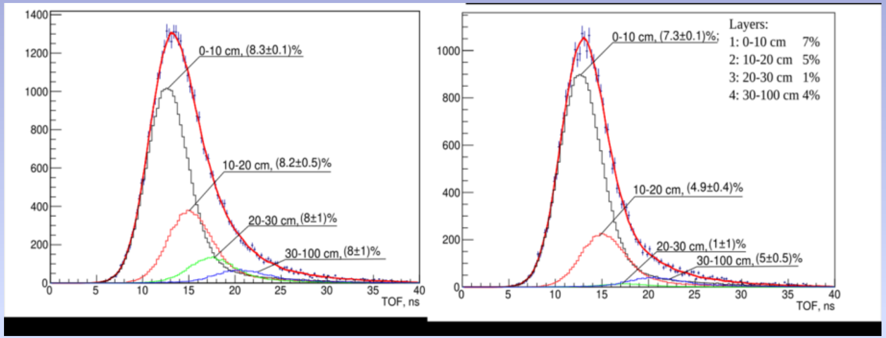




Modeling of an experimental setup for determining the carbon content in soil using the TNM.

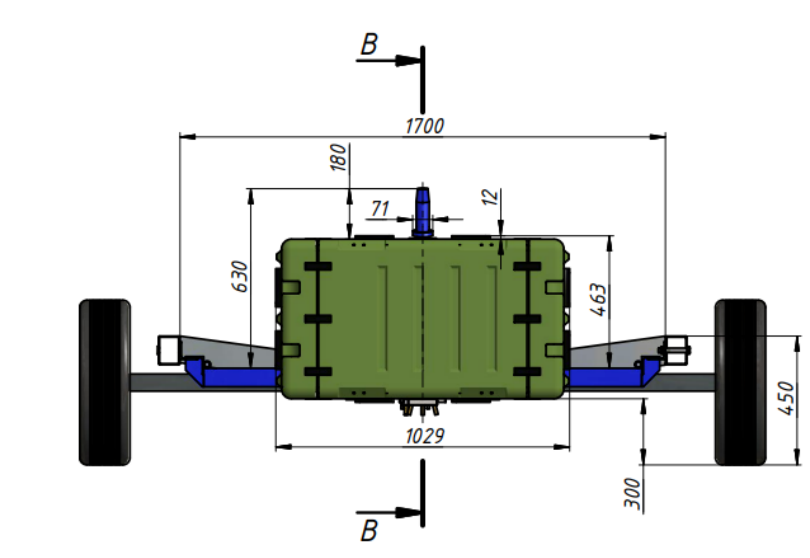


General view of the setup model (left).
Neutron penetration depth profile (right).



Decomposition of the time spectrum into components formed by reactions at different depths for cases with constant (left) and variable (right) carbon concentrations.

Pilot setup for determining the carbon content in soil using the TNM (together with LLC "Diamant")

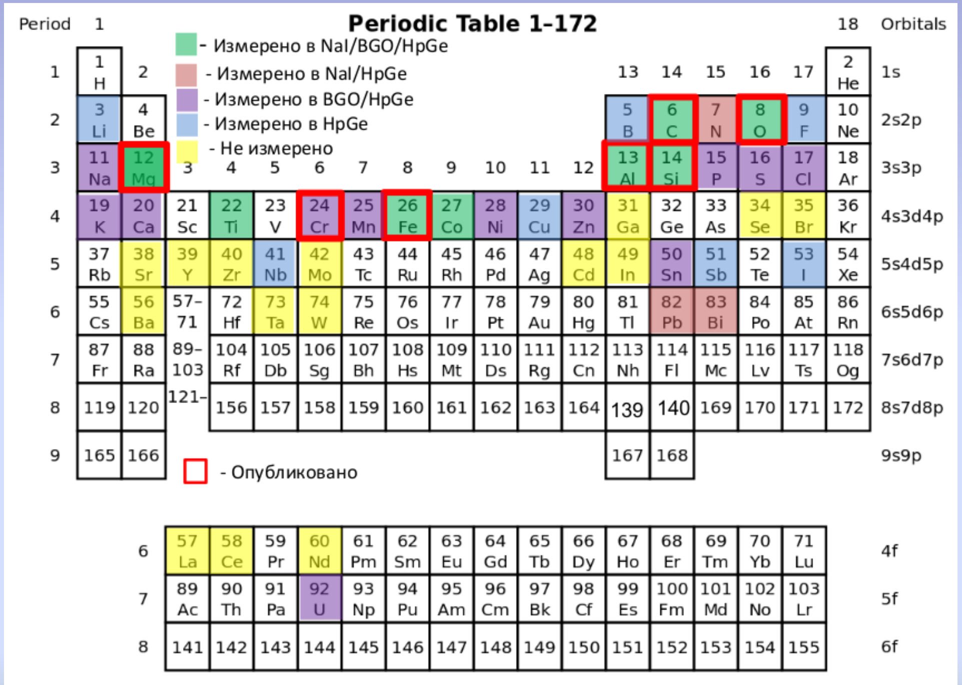


See report of M. Sapozhnikov at ISINN-30

Future ECO-system for soil carbon analysis

Conclusions

The tagged neutron method (TNM) is an effective tool for studying the reactions of fast neutrons with nuclei, which makes it possible to successfully implement a program for measuring differential cross sections of neutron scattering and γ-ray production, as well as a program for the application of the TNM for non-destructive elemental analysis.



Thank you for your attention!