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TAGGED NEUTRON TECHNOLOGY FOR APPLIED AND FUNDUMENTAL NUCLEAR PROBLEMS

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Outline

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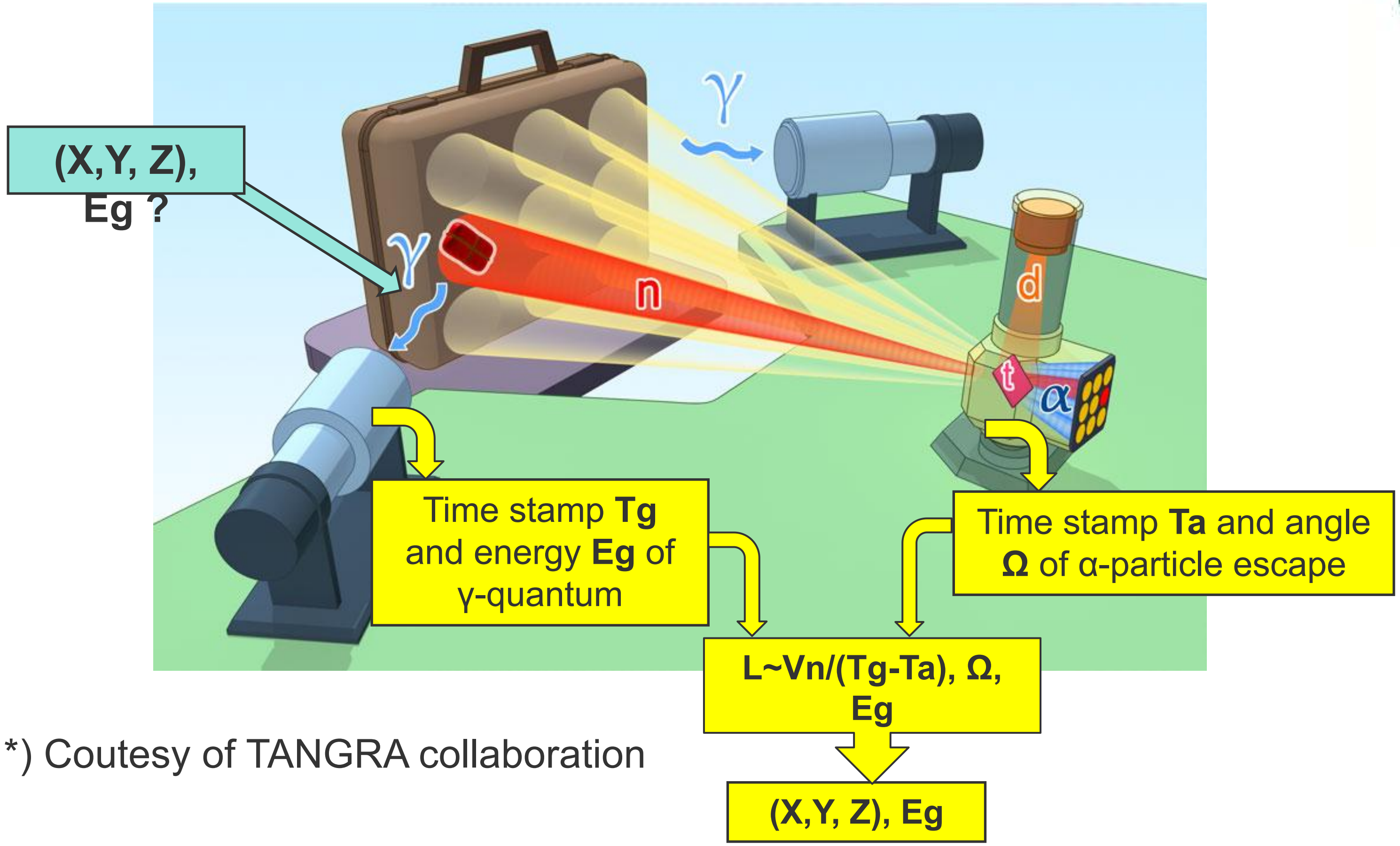
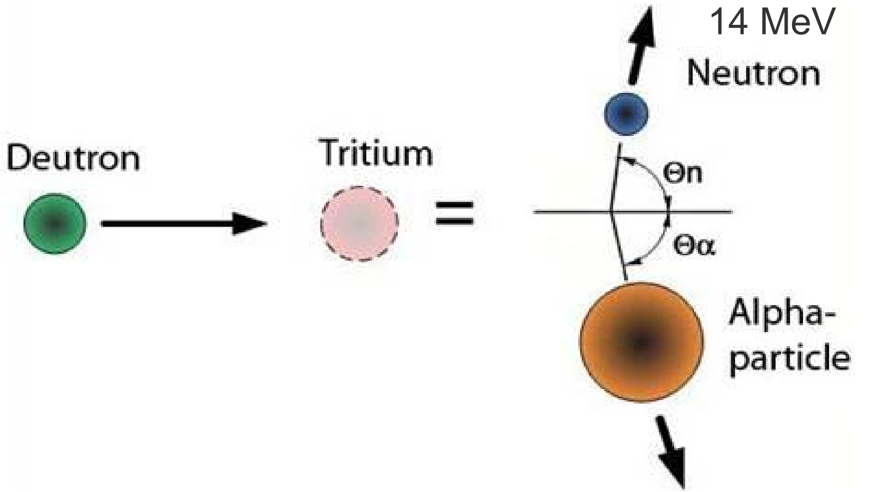
1. Principles and advantages of tagged neutron technology.
2. Study of the Doppler effect in the inelastic neutron scattering and its impact on the gamma-spectra.
3. Measurement of the anisotropy of gamma-rays at the inelastic neutron scattering
4. Estimation of 14 MeV neutron response in non-organic scintillator.
5. Some other tasks.

Tagged Neutron Technology

14 MeV neutron: V_n=5.1cm/ns
3.5 MeV α-particle: V_a=1.3cm/ns
γ-quantum : V_g=30 cm/ns



*) Coutesy of TANGRA collaboration



$$E_d + Q = E_\alpha + E_n,$$

$$p_\alpha^2 = p_n^2 + p_d^2 - 2p_n p_d \cos\theta_{\alpha-d},$$

$$p_n^2 = p_\alpha^2 + p_d^2 - 2p_\alpha p_d \cos\theta_{n-d}$$

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For the first time, the generator of tagged neutrons,, was deviced and applied at the beginning of 50th in VNIIEF (USSR) for the study of fast processes and time-spectral analysis of the gamma- and neutron emission. This work was awarded by Stalin's prize

Today the off-shelf tagged neutron generators are produced in Thermo Scientific, USA (API-120) and VNIIA, RF (ING-27)

Up to date, more than 200 tagged neutron generators ING-27 were produced in VNIIA. They are in the great demand for applied and fundamental nuclear physics, industry, security

Basic advantages of tagged neutron generators

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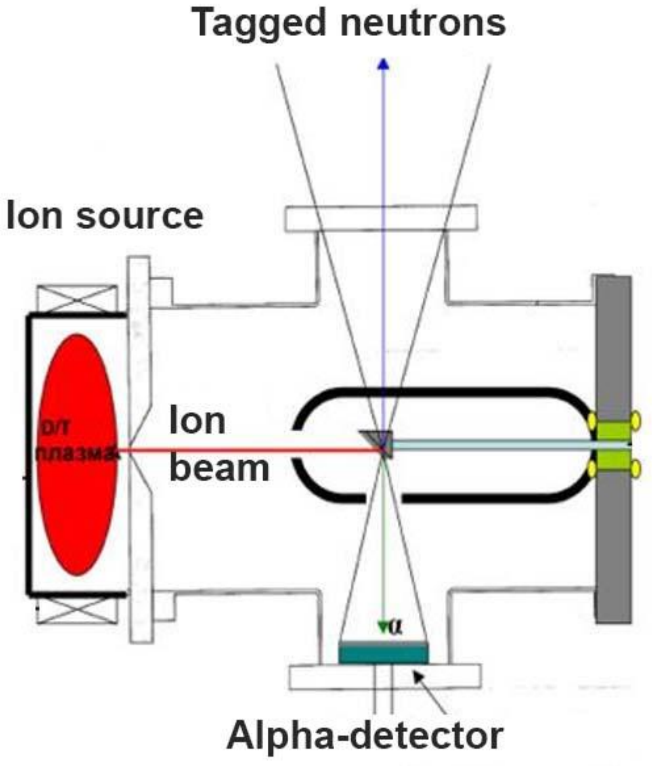
- Monitoring of the neutron generator intensity with the precision as low as 5% (absolute) and 1% (relative) in the wide range by build-in alpha detector.
- Measurement of an angle of 14 MeV neutron escape with the precision as low 0.02 rad and localization of the point of nuclear reaction produced by 14 MeV neutrons with the precision as low as 5-10 cm.
- High effect/background ratio by time-spatial selection of events.
- Possibility of gamma-detectors calibration using :
  - ✓ Special calibrating object located in the flux of tagged neutrons- the emitted gamma-rays can be easily interpreted at the gamma-ray spectrum produced by tagged neutrons;
  - ✓ Standard reference sources – the gamma-lines are well-marked at the total gamma-spectrum but practically does not affect the gamma-ray spectrum produced by tagged neutrons.

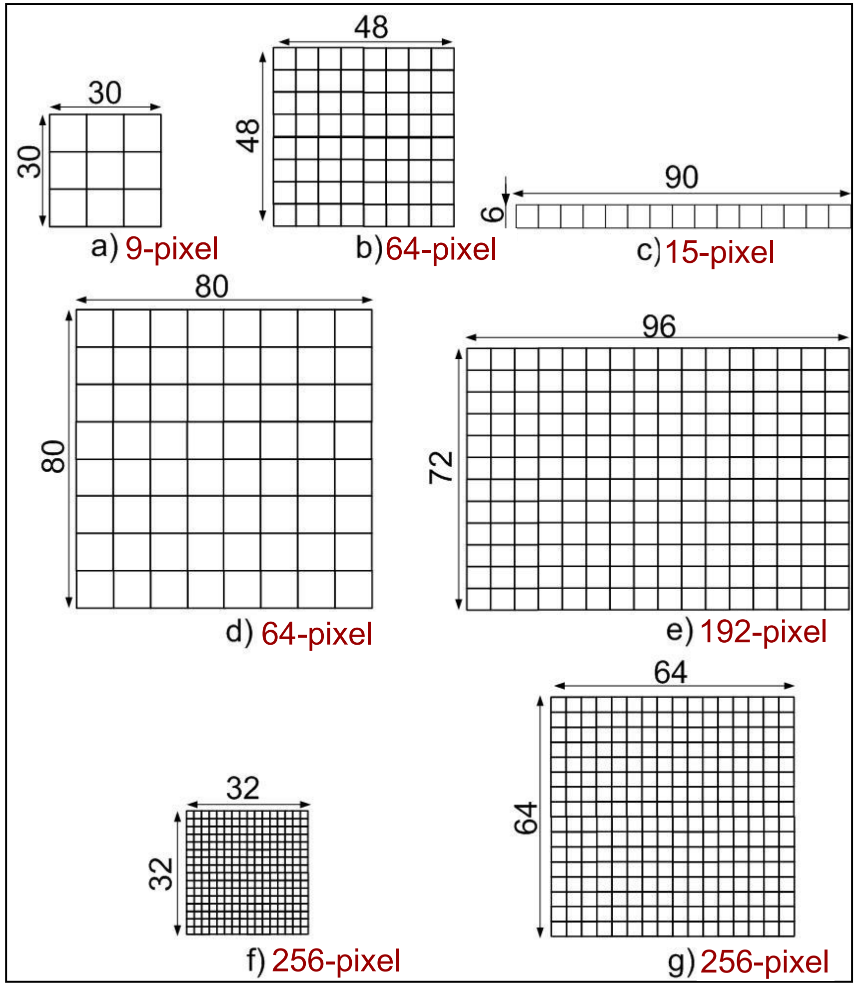
Tagged neutron generators produced in VNIIA



9-pixel alpha-detector

192-pixel alpha-detector

Available configurations of the semiconductor alpha-detector



Amplitude-time spectrums of alpha-gamma coincidences

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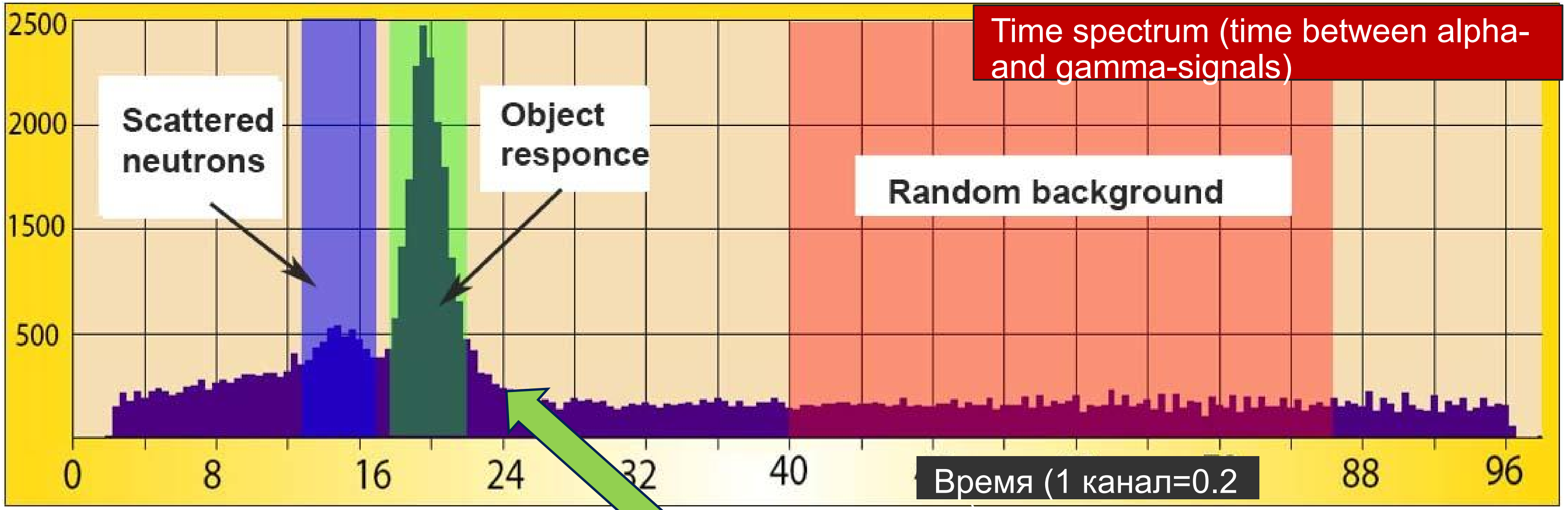

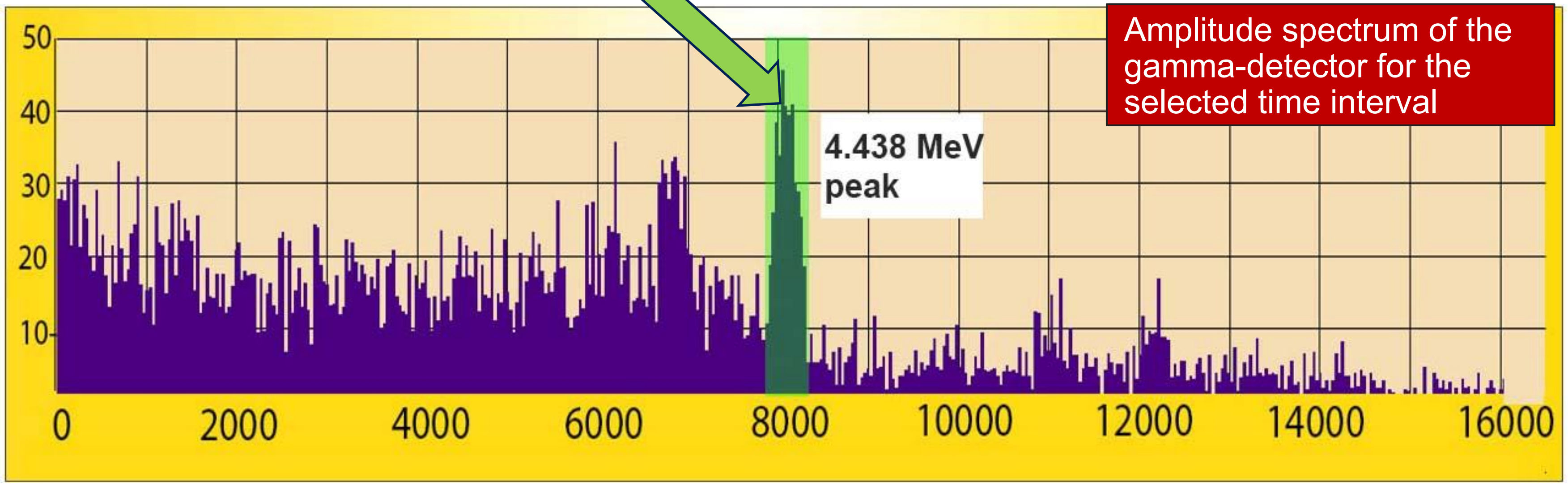

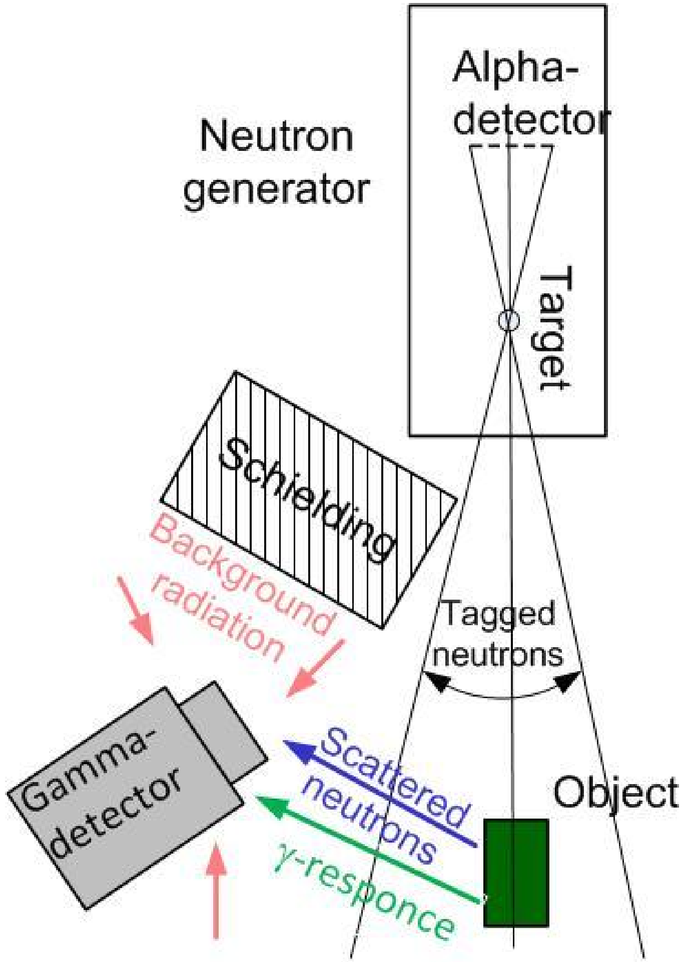

Processing of results of tagged neutron analysis

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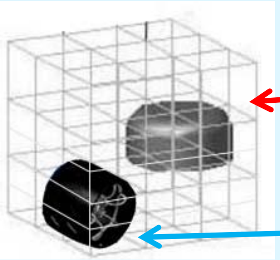
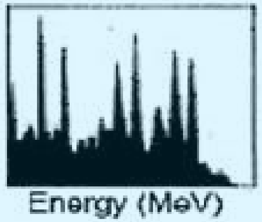
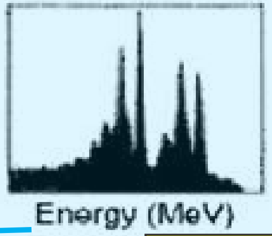
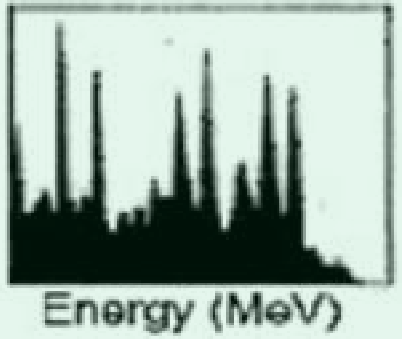
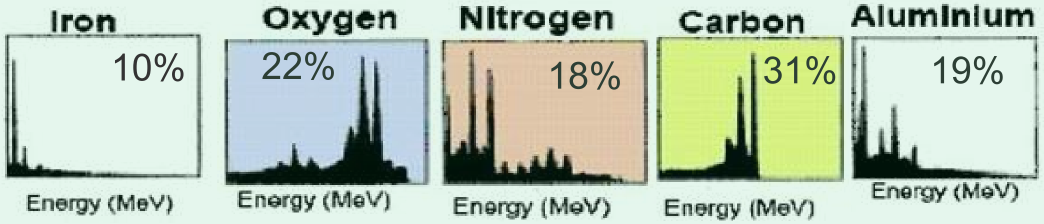




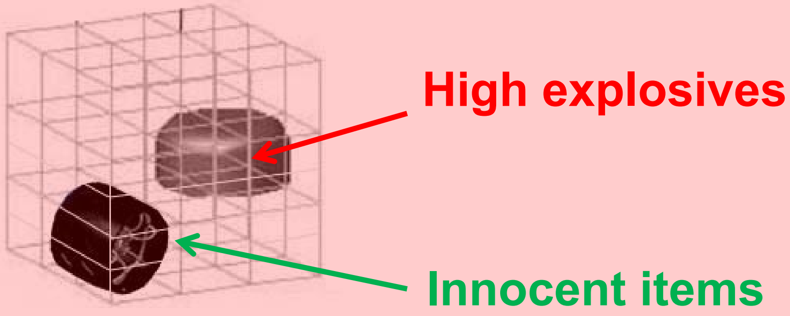


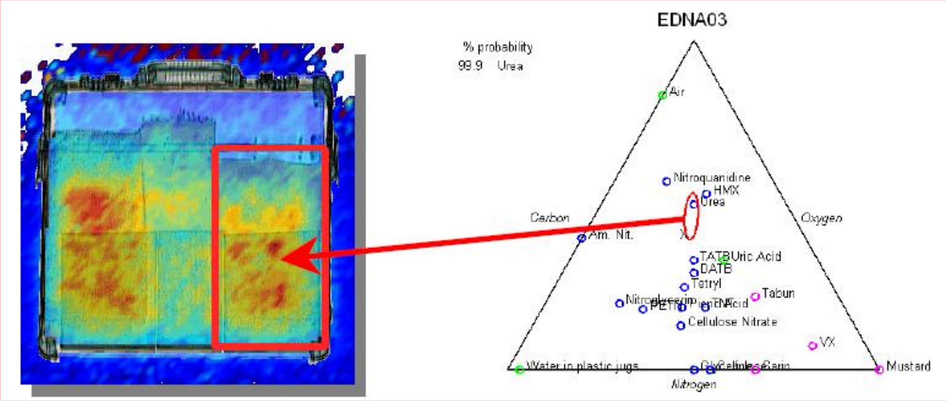
Gamma-spectrum in each voxel





Decomposition of spectrum into elemental spectrums





Decision making algorithm

Influence of inaccuracy of gamma-peak energy determination on the results of spectrum decomposition into elemental spectrums

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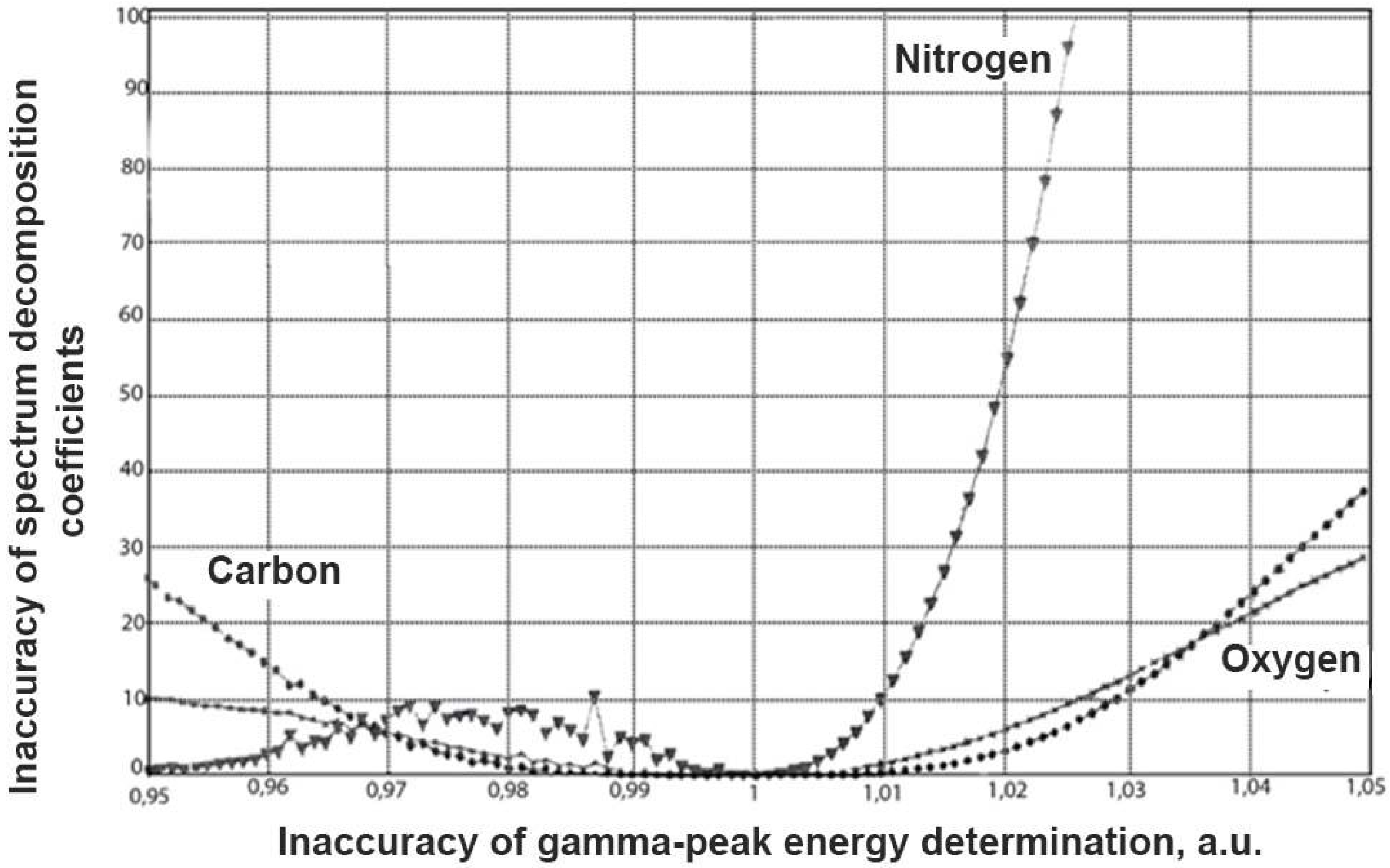

Doppler shift of gamma-detection at the inelastic neutron scattering

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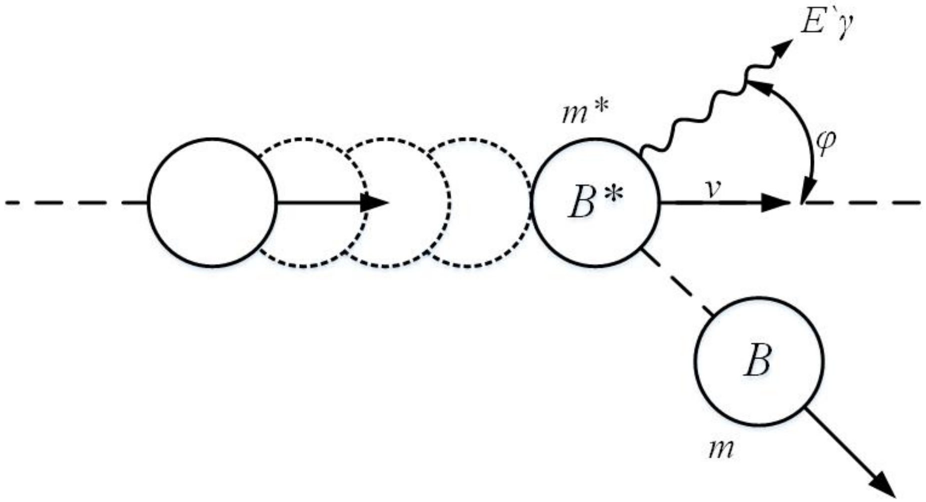
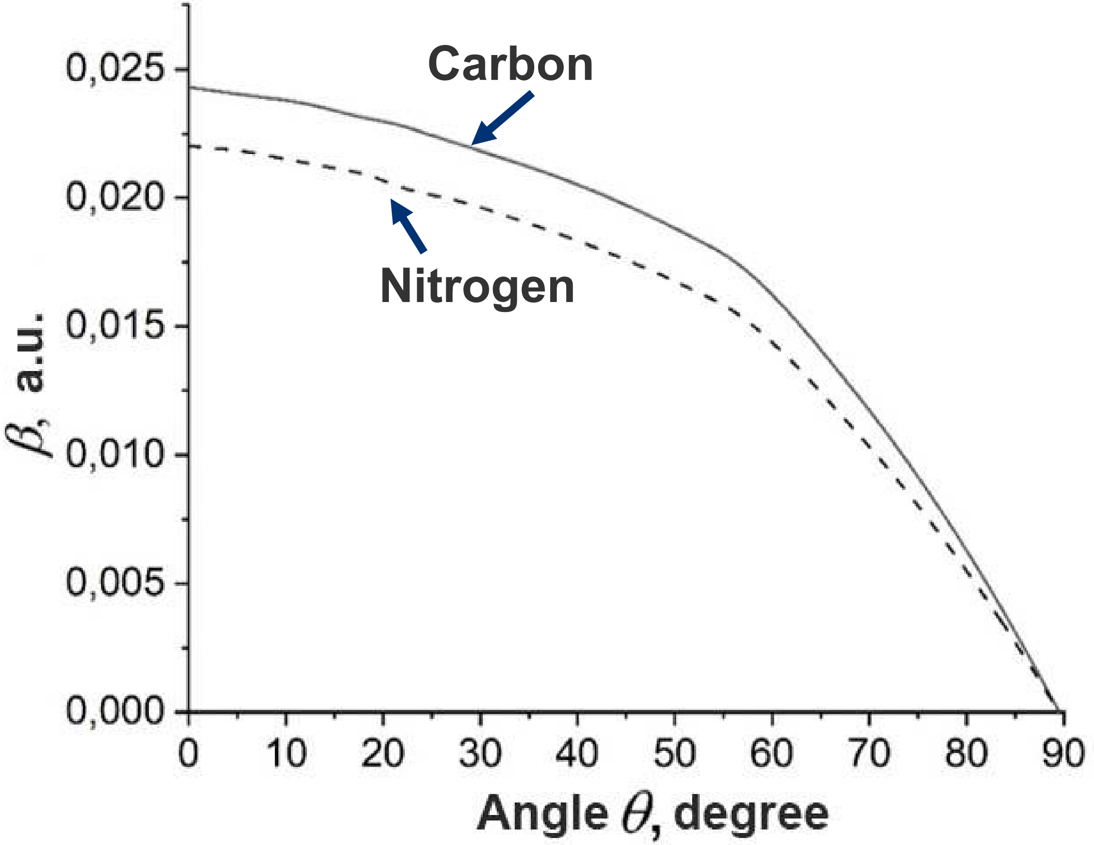


$$E' = \frac{E(E+2mc^2)}{2((E+mc^2)}\sqrt{1-\beta^2}\,\frac{1}{1-\beta\cos\varphi}$$

$$E' = E\beta\cos\varphi$$ (nonrelativistic)



Initial velocity of carbon and nitrogen nuclear after inelastic scattering of 14MeV neutron

Doppler shift of gamma-detection at the inelastic neutron scattering

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$$E' = E\beta\cos\varphi$$

Nucleus	Cross-section of (n,n',γ) reaction, mbarn	Energy transition, MeV	$T_{1/2}$, fs	E_γ, MeV
C-12	184	4.439.82 (2^+) →0.0 (0^+)	42.2	4.438
N-14	69	2.312798 (0^+) → 0.0 (0^+)	6.8	2.315593
	42	5.10589 (2^-) → 0.0 (0^+)	4350	5.10489
O-16	173	6.12989 (3^-) → 0.0 (0^+)	18400	6.12863
	53	6.91710 (2^+) → 0.0 (0^+)	4.7	6.9155
	73	7.11685 (1^-) → 0.0 (0^+)	8.3	7.11515

Chart of Nuclides. Basic Properties of Atomic Nuclei.–[Электронный ресурс]. URL: https://www.nndc.bnl.gov/nudat3/)

For gamma-peaks of 2.316 MeV (N-14) and 4.438 (C-12) MeV:
Maximal velocity of C-12 and N-14 β=v/c=0.02-0.016
Slowing-down time $T_{sl} \approx 1$ ps

When $T_{sl} >> T_{1/2}$ ⟶ Doppler shift

Doppler effect influence on the gamma-spectrums

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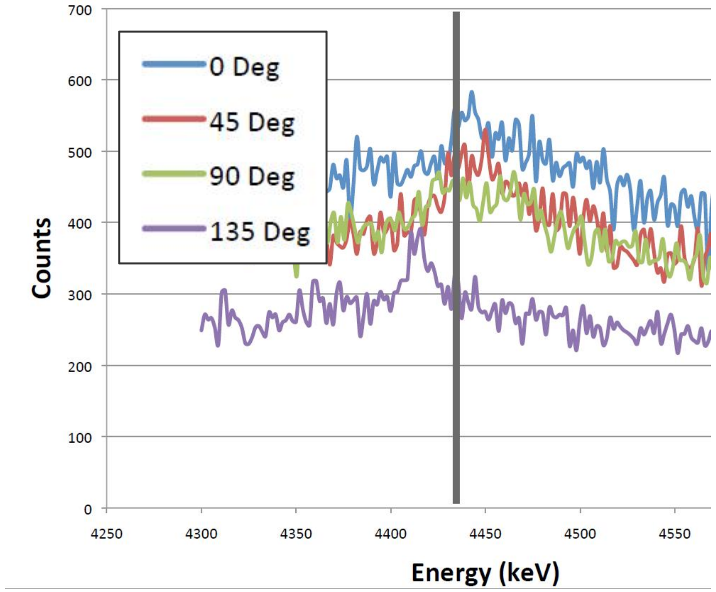
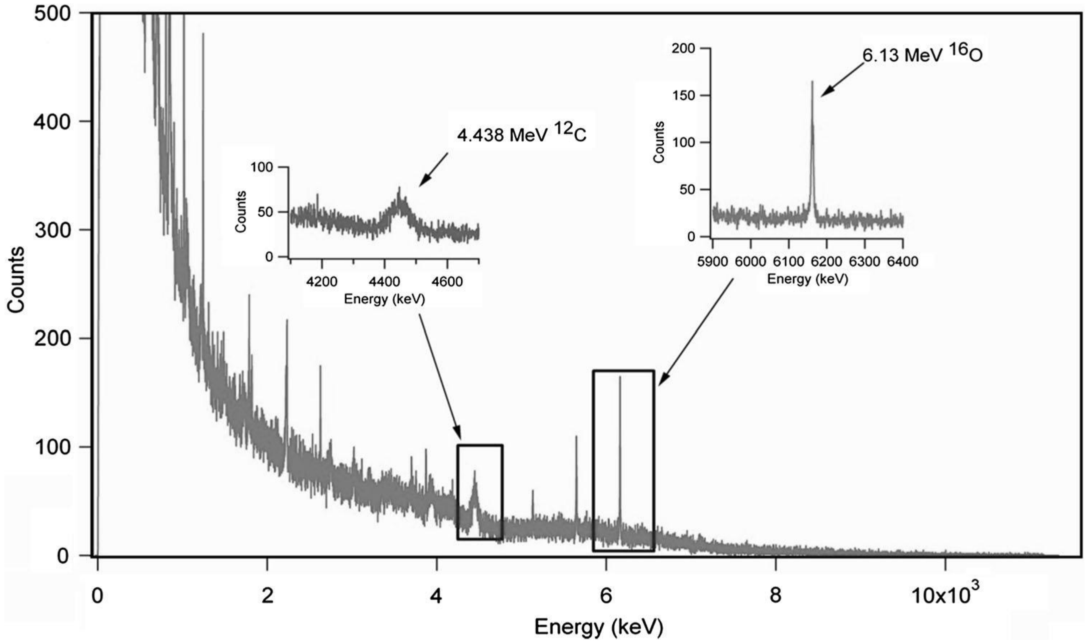
Gamma-peak shift at various angles

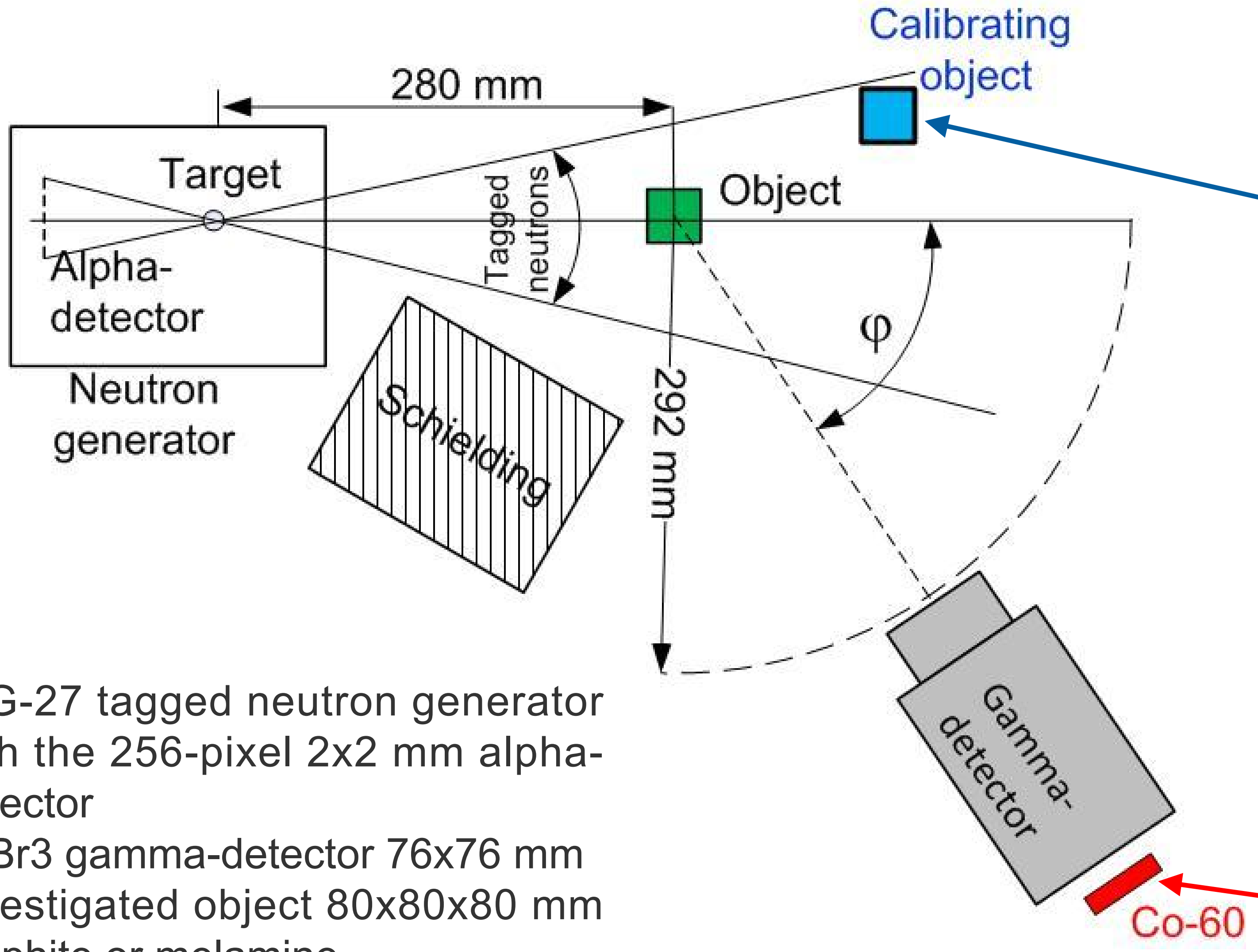


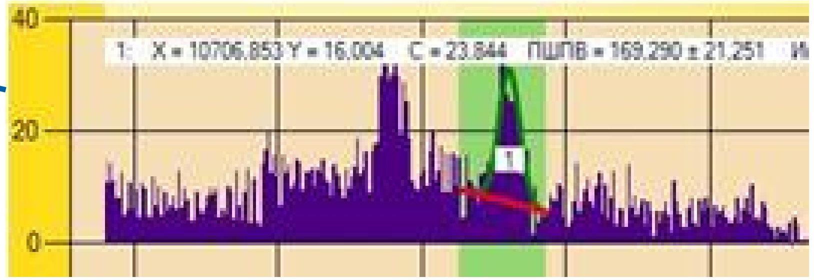
Spectrum broadening



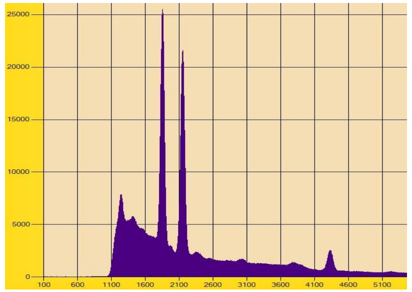
**Whitfield D. Doppler-Broadening of Light Nuclei Gamma-Ray Spectra. Masters Theses & Specialist Projects. Paper 1075 (2010).*

Experimental setup for measuring Doppler shift





Calibration by gamma-peaks at inelastic neutron scattering in oxygen (water)



Calibration by Co-60 peaks

- ING-27 tagged neutron generator with the 256-pixel 2x2 mm alpha-detector
- LaBr3 gamma-detector 76x76 mm
- Investigated object 80x80x80 mm graphite or melamine
- Calibrating object 80x80x80 mm water filled container

Doppler shift and broadening at the inelastic neutron scattering on carbon and nitrogen nuclei

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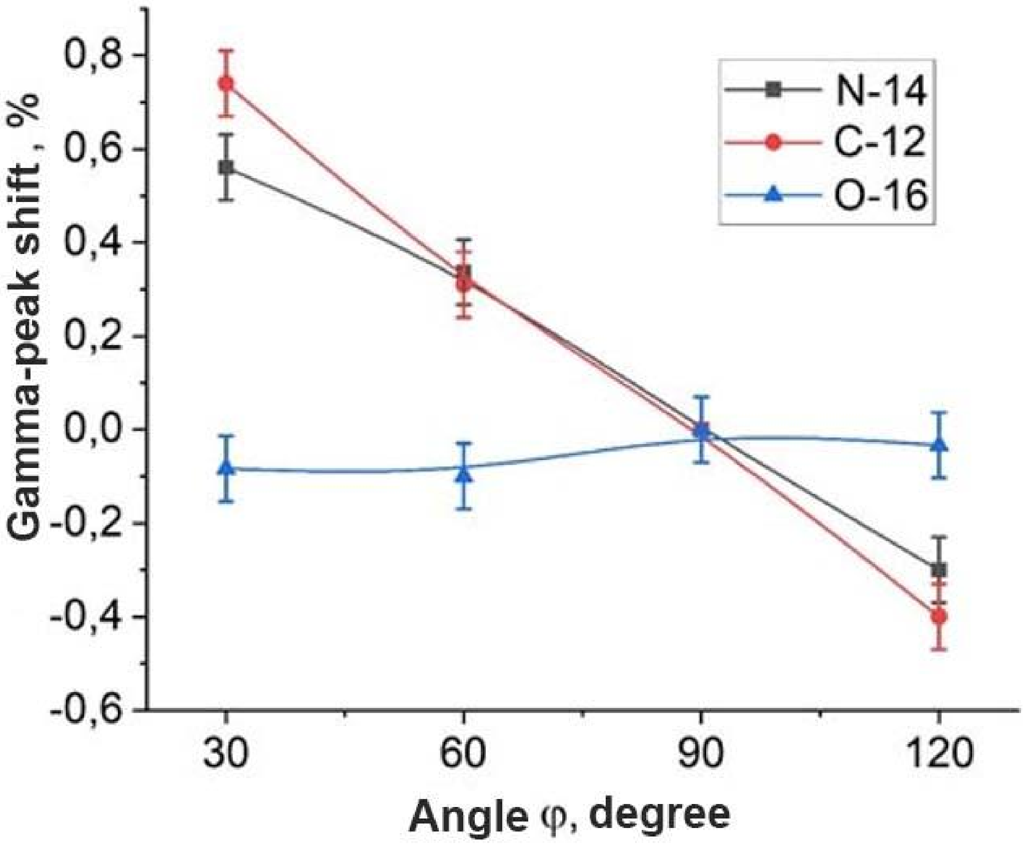
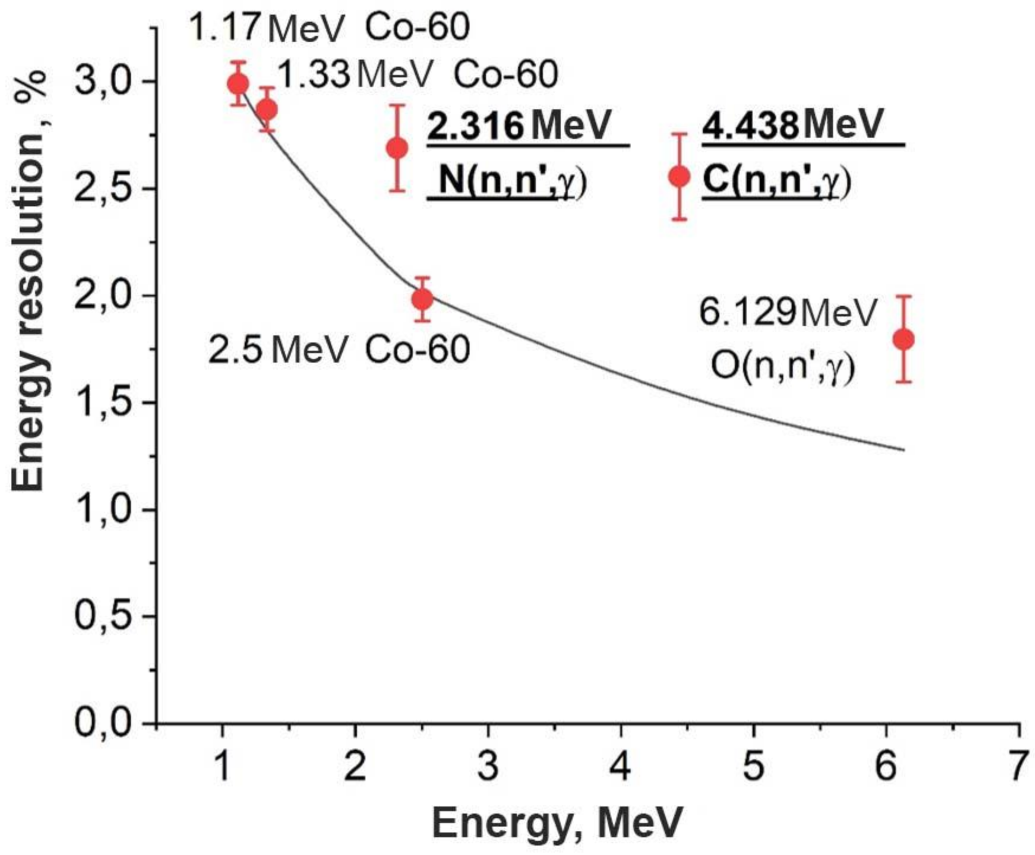
Gamma-peak shift vs angle between neutron and gamma-quantum vectors of movements



Energy resolution of $LaBr_3$ (broadening of carbon and nitrogen gamma-peaks)



Experimental setup for measuring anisotropy of gamma-rays at the inelastic neutron scattering

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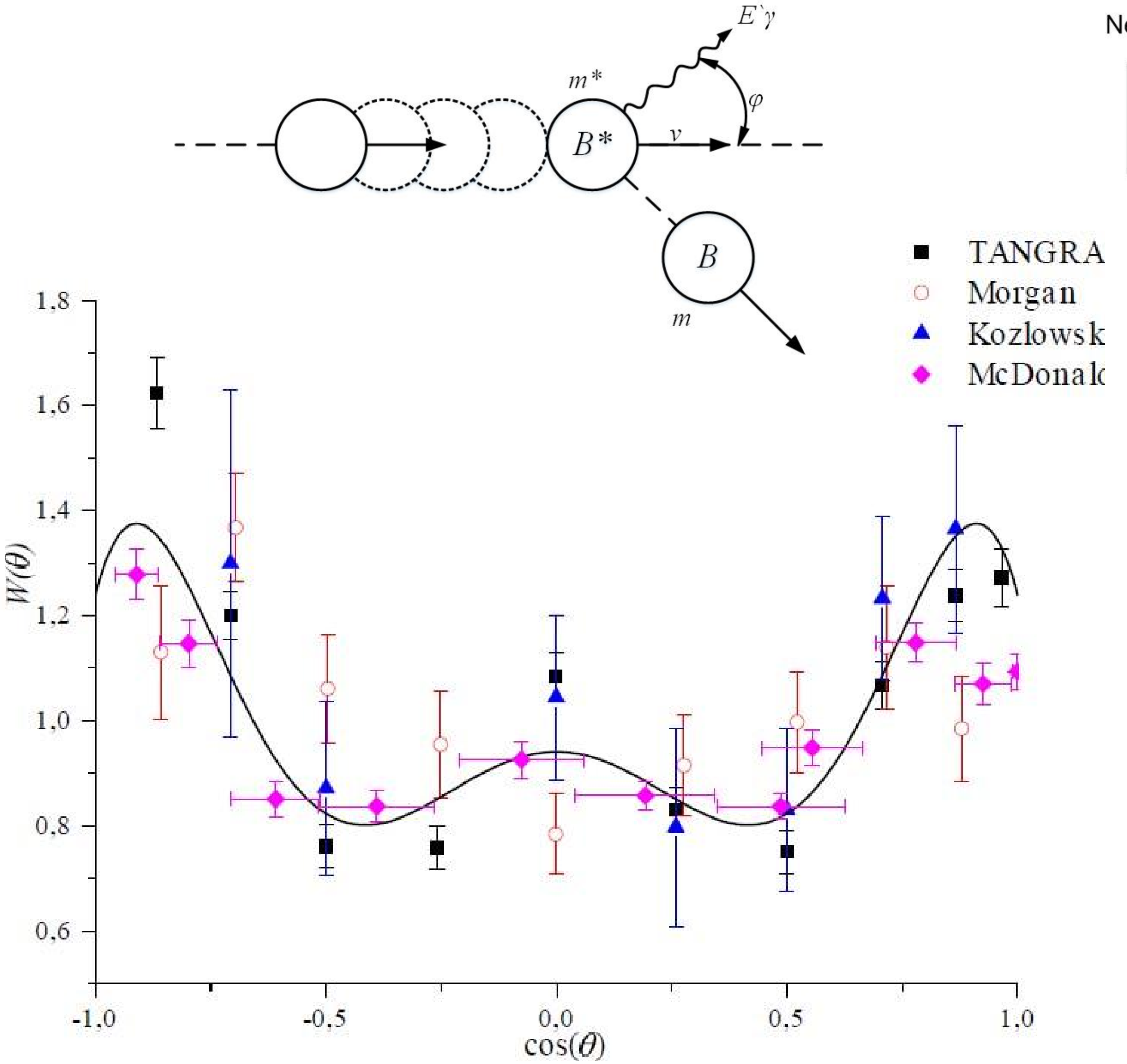
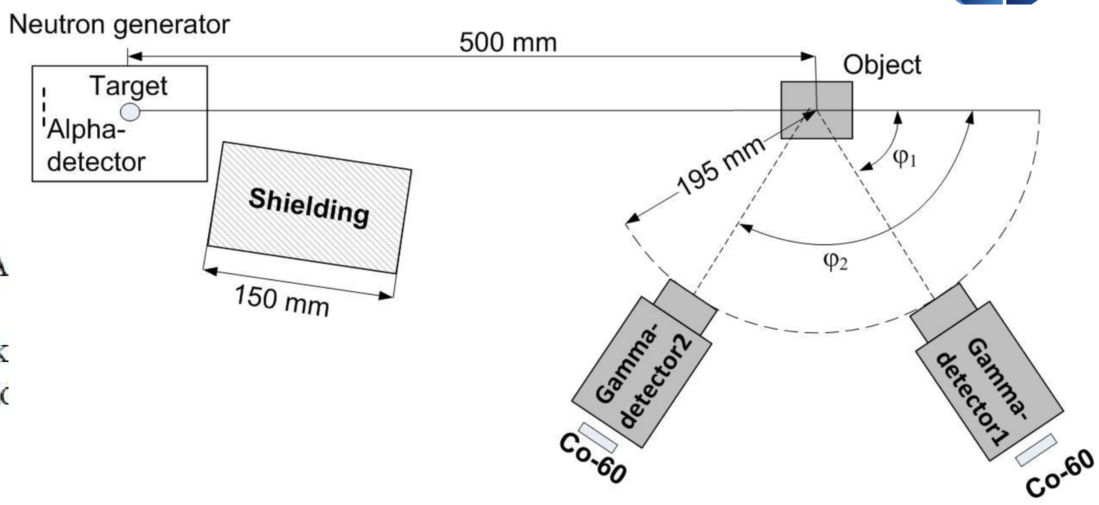
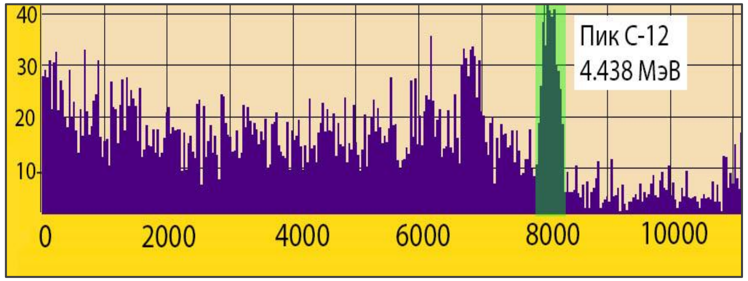




- ING-27 tagged neutron generator with the 256-pixel alpha-detector
- LaBr3 gamma-detector 76x76 mm
- Object 80x80x80 mm containers filled by graphite, melamine, water

Measurement of peak area, normalized by the tagged neutron flux



Angle distribution of gamma-rays at the inelastic neutron scattering by nitrogen, carbon, and oxygen nuclear

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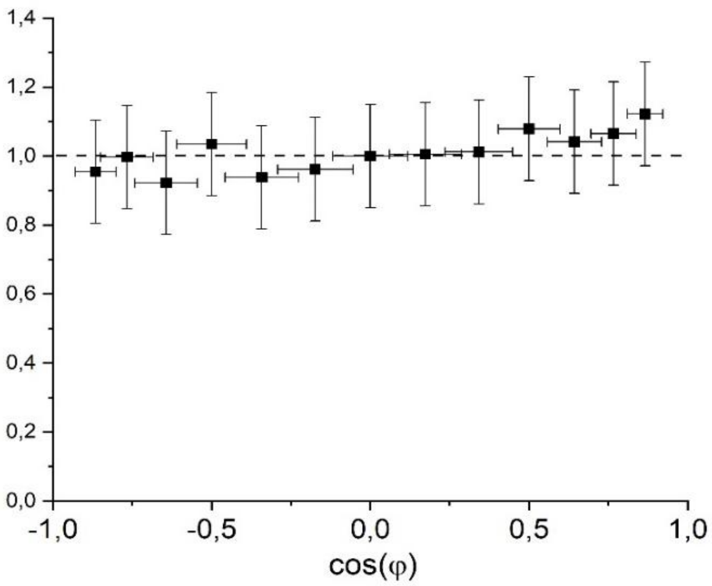
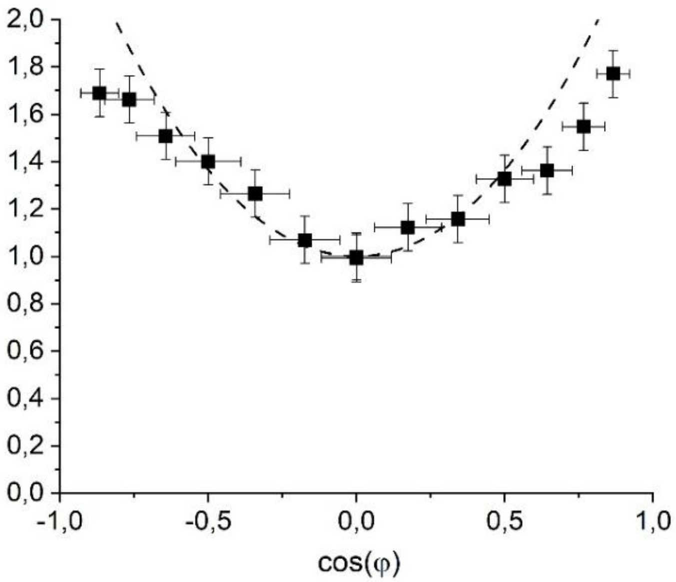
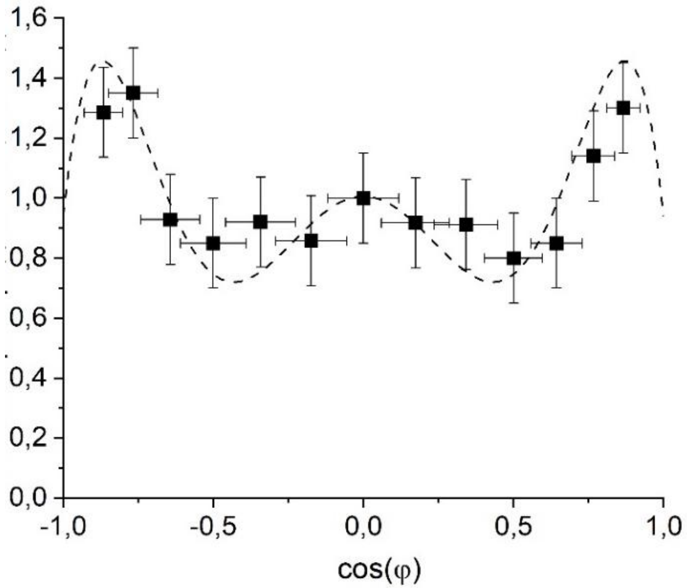
Nitrogen (2.316 MeV peaks)



Carbon (4.438 MeV peaks)



Oxygen (6.129 MeV peaks)



Dashed-line curve–ENDF approximation

Gamma-spectroscopy at high neutron background

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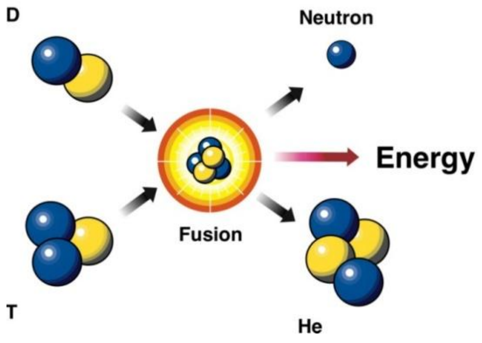
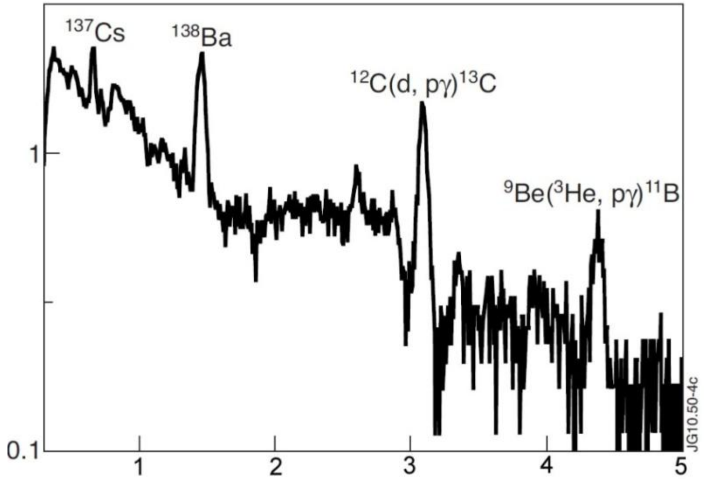
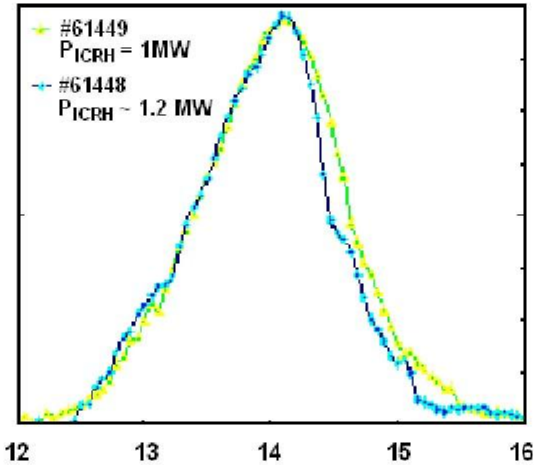
Application: Gamma-spectroscopy of thermonuclear plasma

Diagnostic information :
1. Temperature of fast ions (spectroscopy)
2. MHD instabilities (count rate)
3. Impurities assessment





Gamma-ray energy, MeV



Neutron energy, MeV

Need to separate signal from neutron background in DT plasmas

Processing of gamma-spectroscopy at high neutron background

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1. Recording the mixed gamma-neutron spectrum M(E).
2. Measurement of neutron spectrum $S(E_n)$ by neutron detectors.
3. **Determination of gamma-detector response $R(E, E_n)$ on incident neutrons with $S(E_n)$ spectrum.**
4. Assessment of neutron contribution to mixed gamma-neutron spectrum N(E).
5. Deduction of neutron contribution N(E) from mixed gamma-neutron F(E).

Reaction induced by 14 MeV neutrons in scintillators

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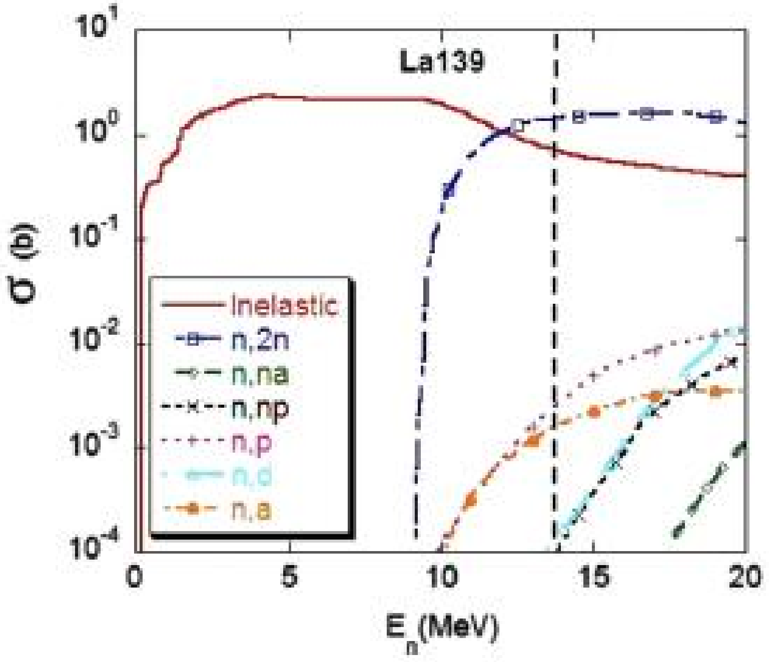
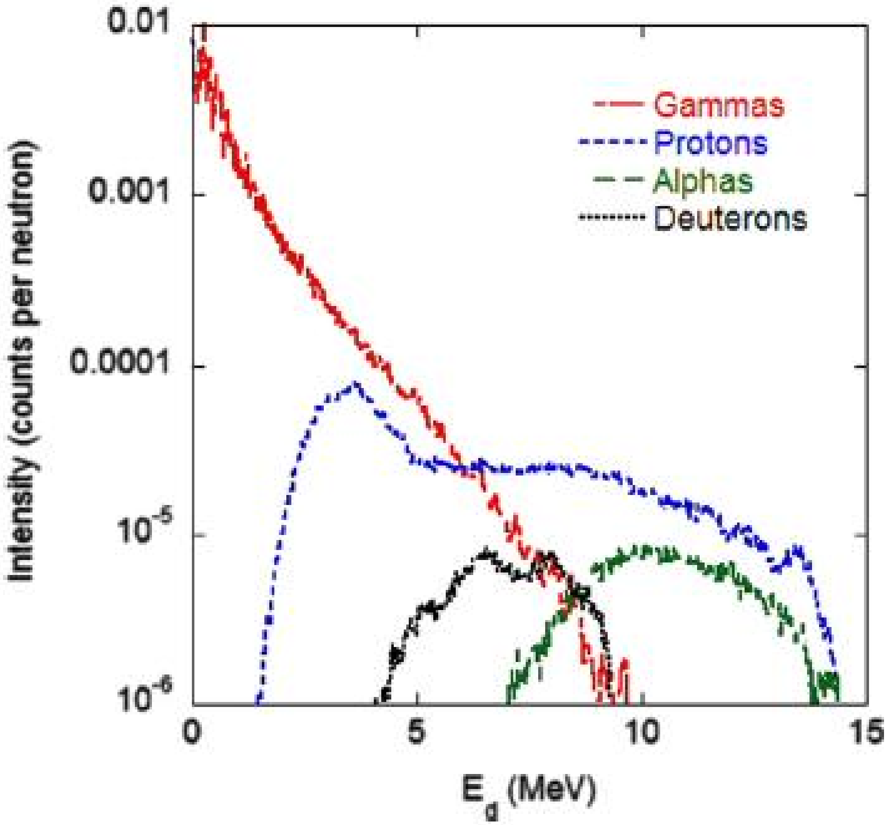


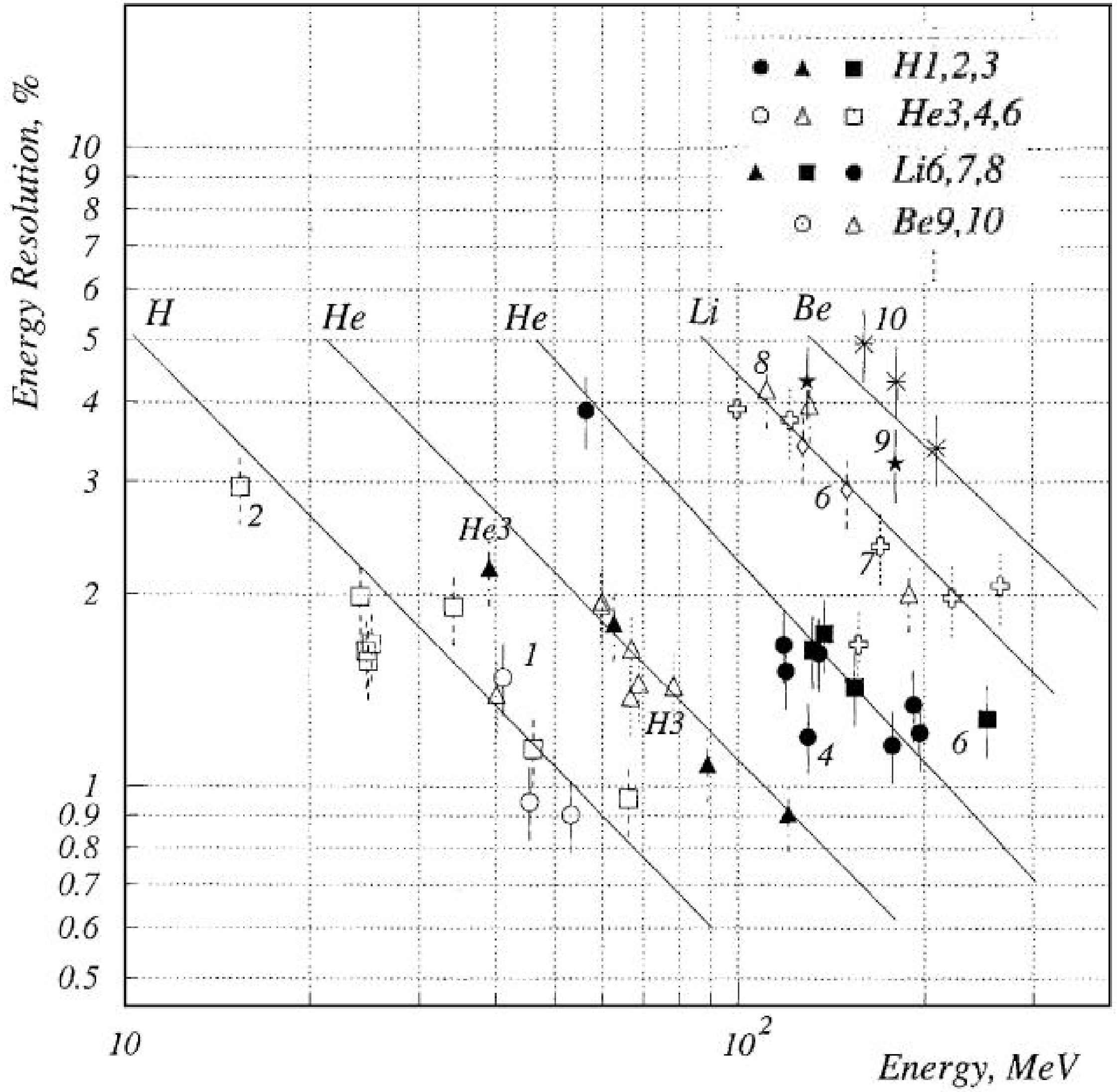


Gamma creation	1.178
Neutron creation (n,2n)	4.513×10^{-1}
Proton creation	9.54×10^{-3}
Deuteron creation	7.63×10^{-4}
Alpha creation	1.10×10^{-3}

C. Cazzaniga et al. Response of LaBr3(Ce) scintillators to 14 MeV fusion neutrons, NIM A778 (2015) 20–25

Light output variations in crystals

(dependant on the quality of crystal material and fabrication technology)



Birks equaition

$$dL/dx = \text{const.}\frac{dE/dx}{1 + kB\,dE/dx}$$

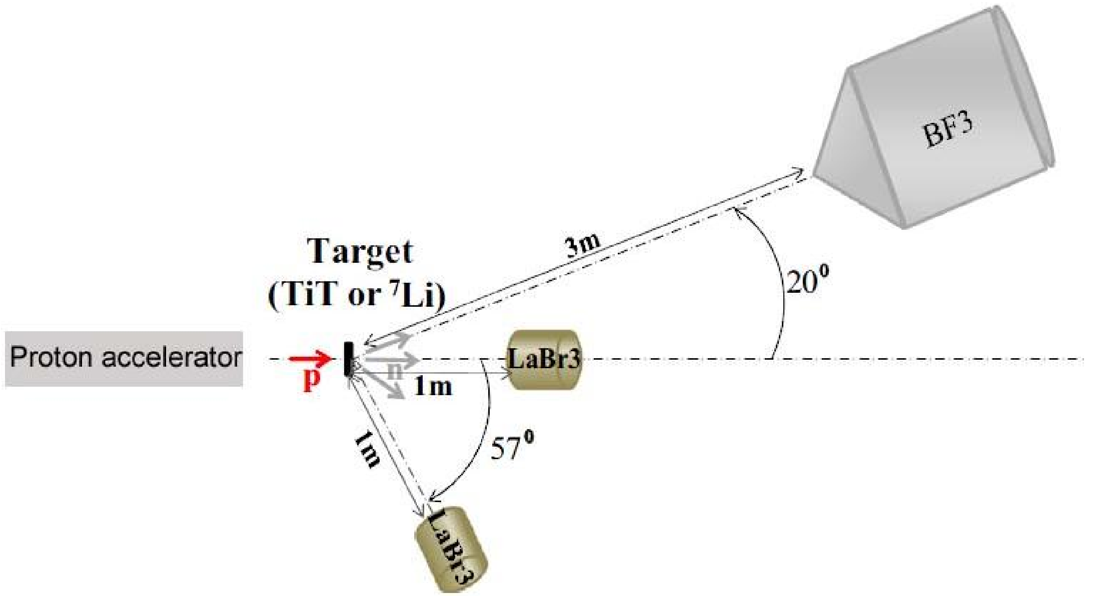
$$dE/dx \simeq c\frac{AZ^2}{E}$$

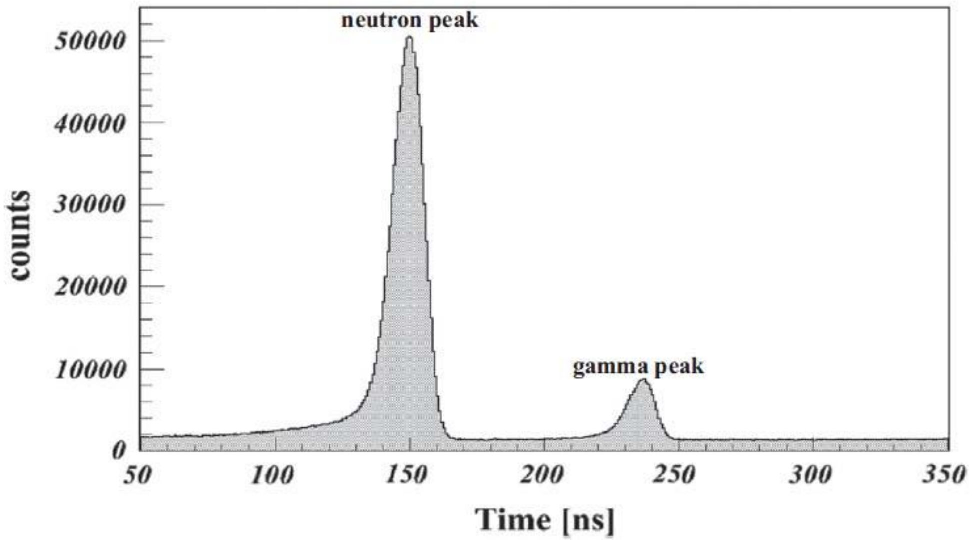
Light output vs particle parameters

$$L(E, A, Z) = a_1\left(E - a_2 AZ^2 \ln\left|\frac{E + a_2 AZ^2}{a_2 AZ^2}\right|\right)$$

V. Avdeichikov et al. Range-energy relation, range straggling and response function of CsI(Tl), BGO and GSO(Ce) scintillators for light ions, NIM, A 439 (2000)

Time-of-Flight Technique





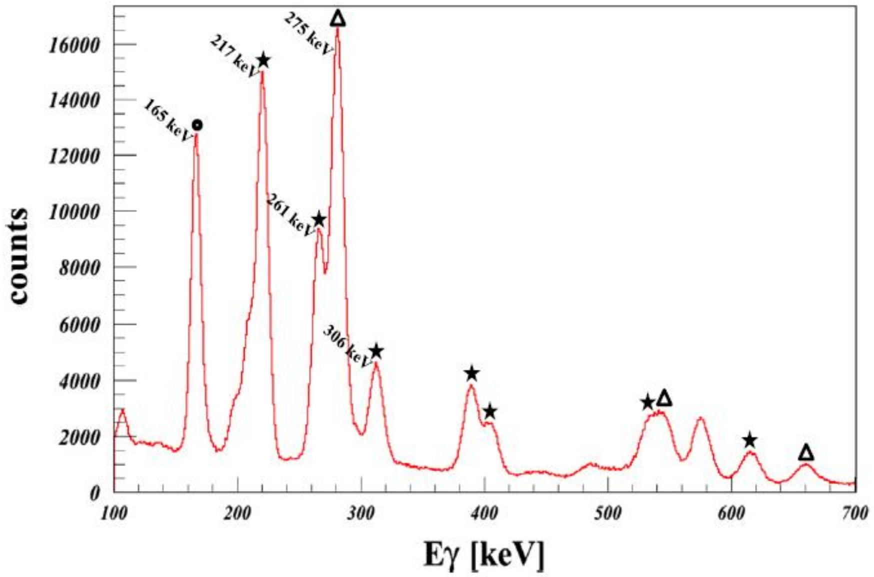
Advantages:

Wide range of neutron energies

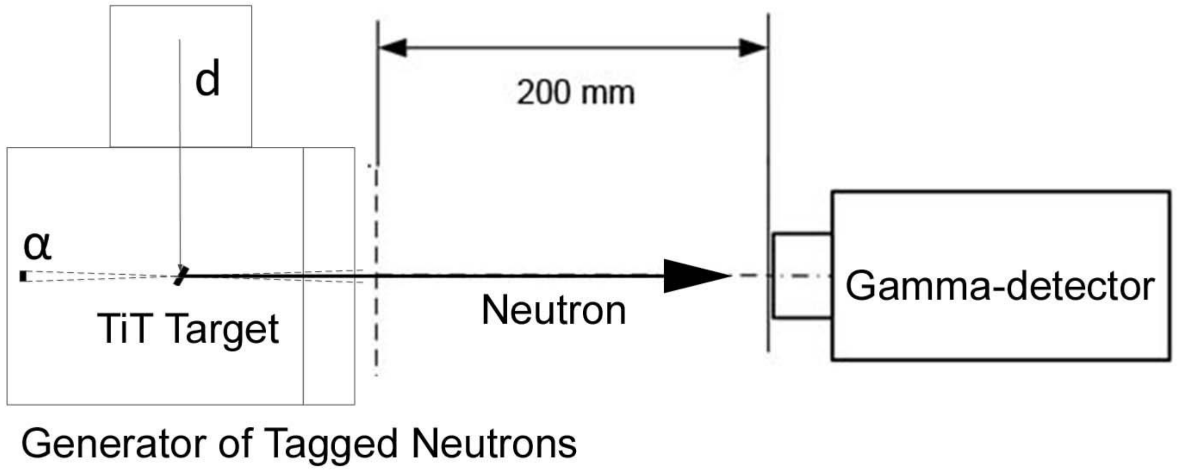
Disadvantages:

High cost, difficulty to access

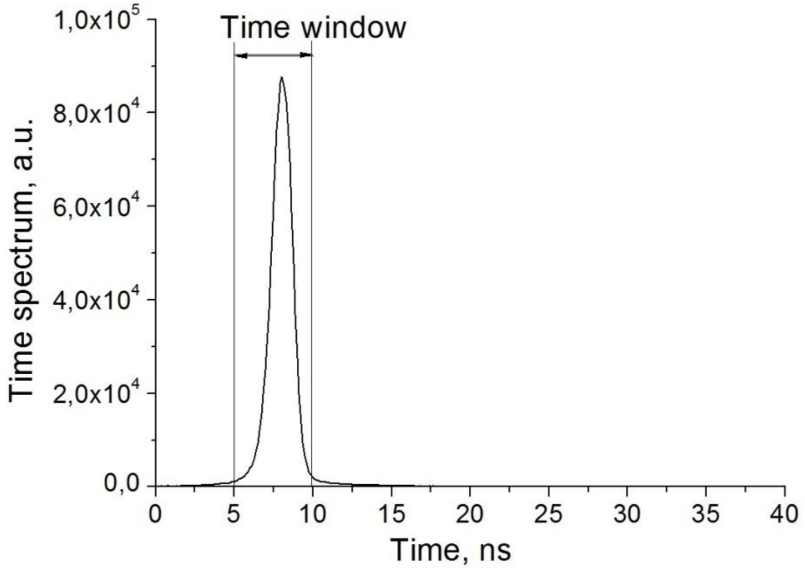
Durational to avoid overlapping of neutron induced pulses in gamma-detectors

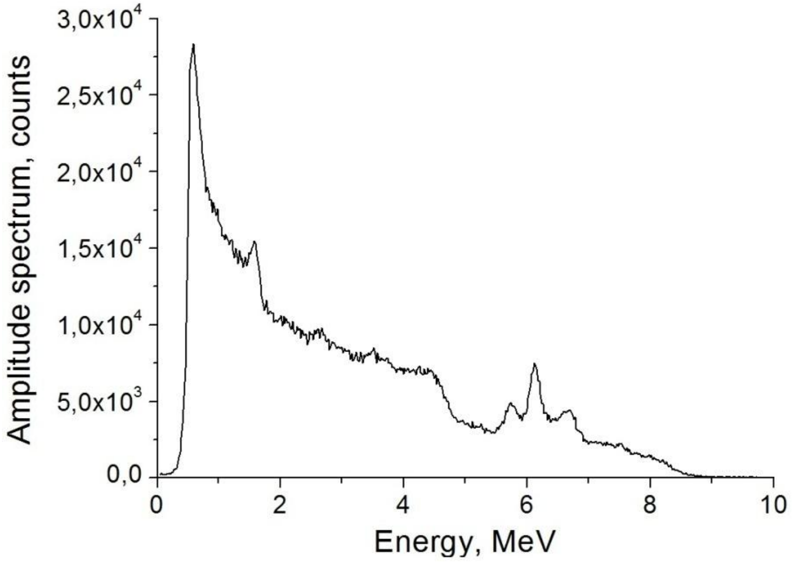


Experiments on measuring gamma-detectors response to 14 MeV neutrons



Time and amplitude spectra of alpha-gamma coincidences





Energy spectra of gamma-detectors normalized for 1 neutron

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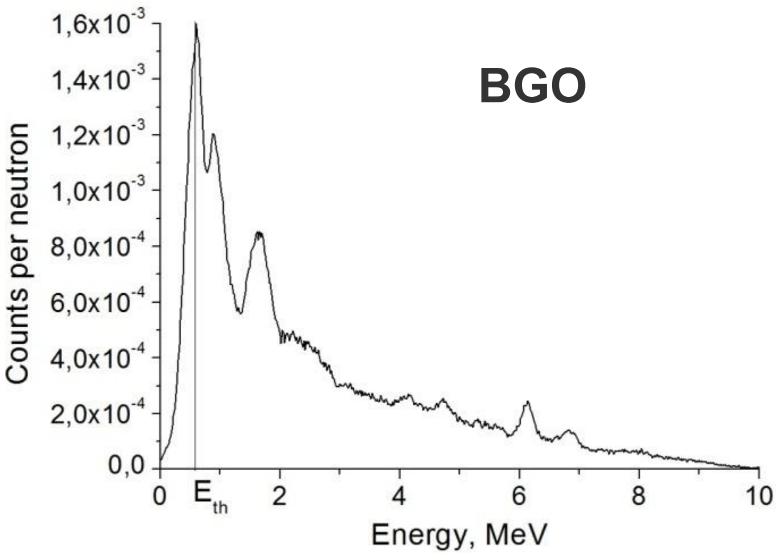
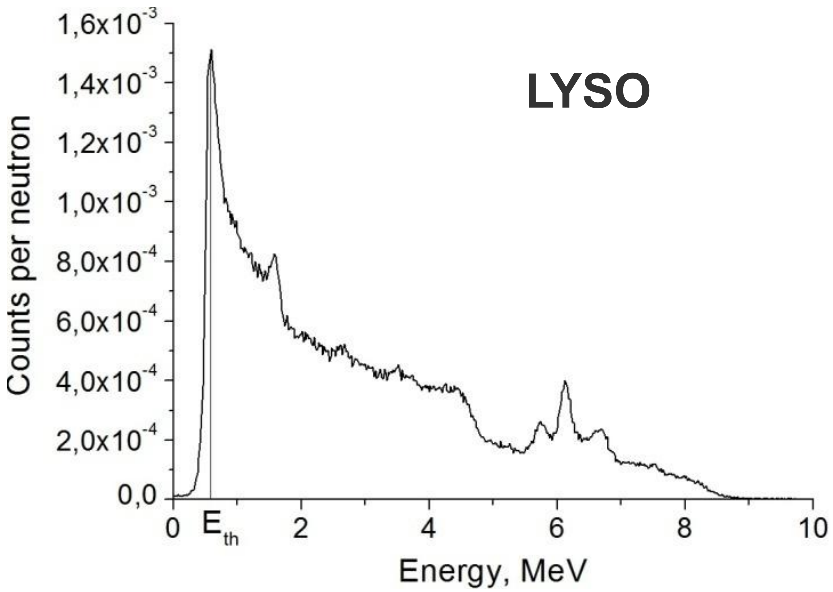
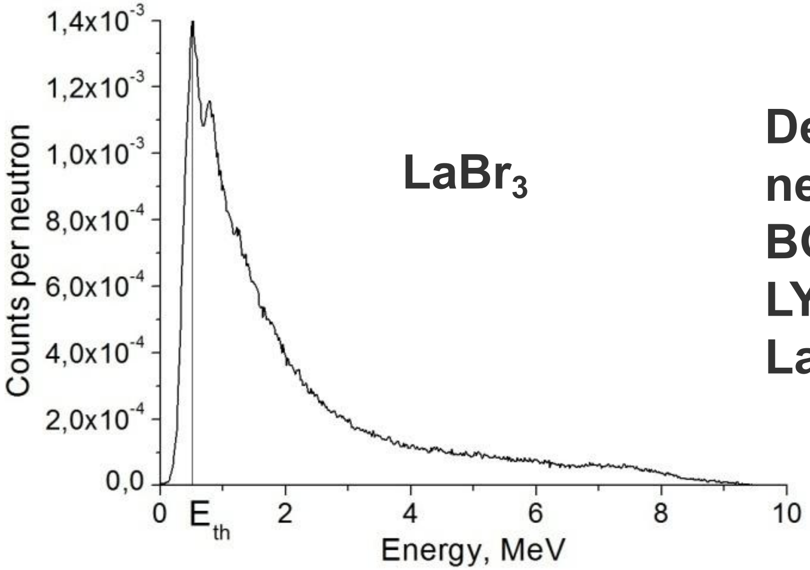
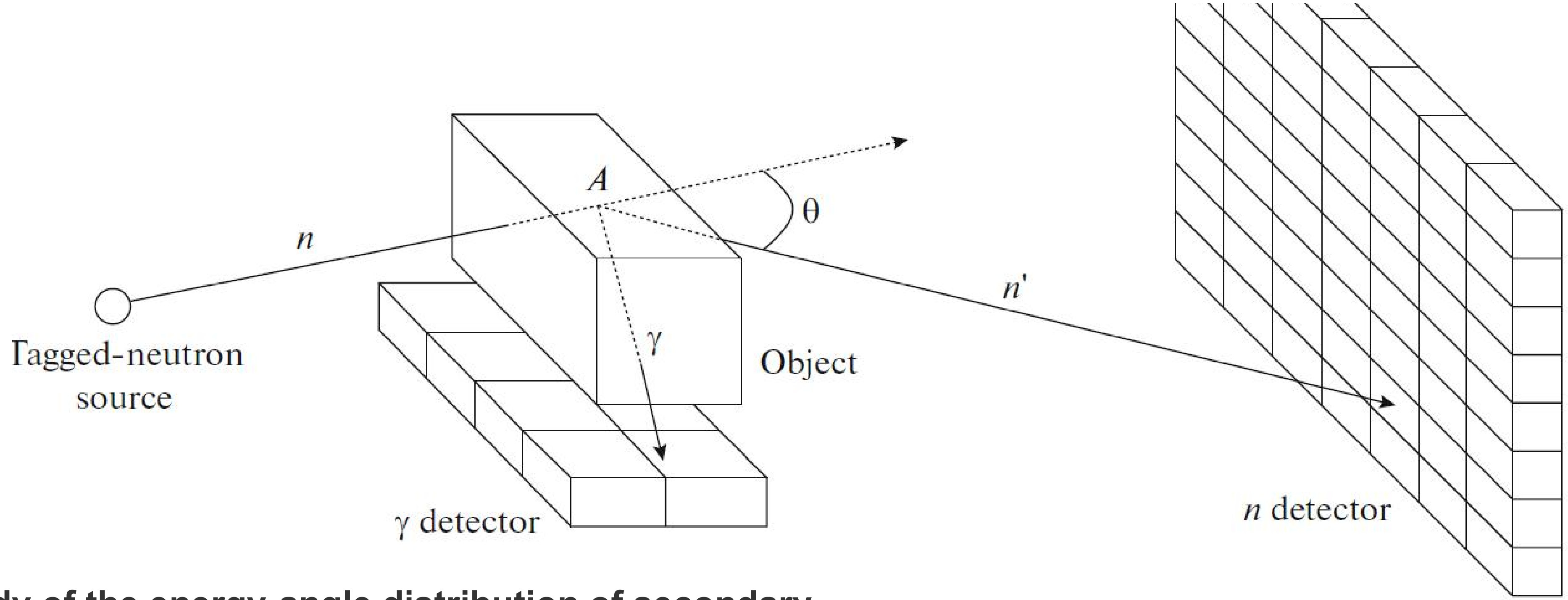






Detection efficiency for 14-MeV neutrons (0.6 MeV threshold):
BGO - 0.50
LYSO - 0.56
$LaBr_3$ - 0.40

Tagged neutron devices with recording alpha-neutron coincidences



- Study of the energy-angle distribution of secondary neutrons at the inelastic neutron scattering
- Elemental analysis via recording alpha-neutron coincidences
- Pure source of 14 MeV neutrons for testing and calibration of detectorsgamma-neutron with discrimination

$$E_n = \left(\frac{a}{2} \cos\theta + \frac{1}{2}\sqrt{a^2 \cos^2\theta + 4b} \right)^2,$$

$$a = \frac{2}{M+1}\sqrt{E_0}, \quad b = \frac{M-1}{M+1}E_0 - \frac{M}{M+1}U,$$

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