Angular correlation of gamma-rays in the inelastic scattering of 14 MeV neutrons on carbon

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for the TANGRA collaboration

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Motivation: why to measure angular correlations in the inelastic scattering of neutrons

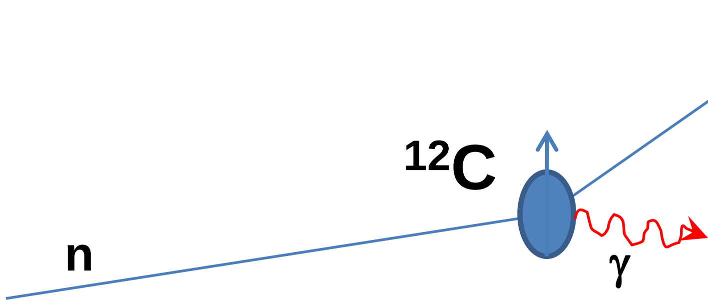
- Commissioning of the TANGRA setup

- Some discrepancies between available experimental data

- Investigate possible differences between neutron and proton scattering

- Angular anisotropy of the emitted gamma-rays has to be taken into account if the tagged neutron method is used for elemental analysis

Theoretical considerations



In general case, the angular distribution is described by:

$$W(\theta_\gamma, \phi_\gamma) = \sum_\nu P_\nu \sum_{mm'} \alpha_m(\nu)\alpha_{m'}(\nu) X_{2m} \cdot X_{2m'},$$

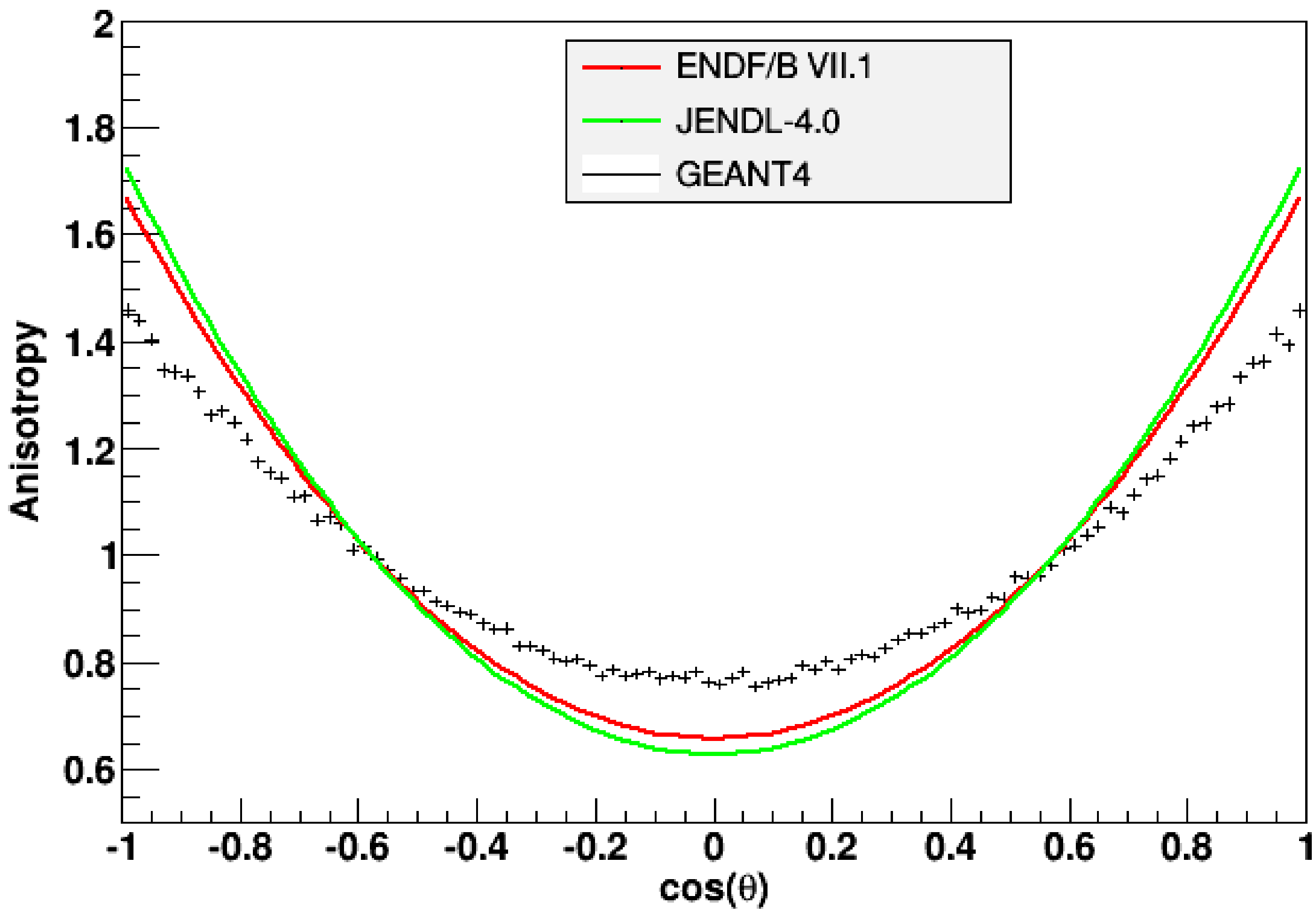
Where

- θ, φ - polar and azimuthal angle of the gamma emission;
- P_ν - probability that mode ν is formed;
- $\alpha_m(\nu)$ – amplitude of the corresponding m-component
- X_{2m} – normalized spherical harmonic

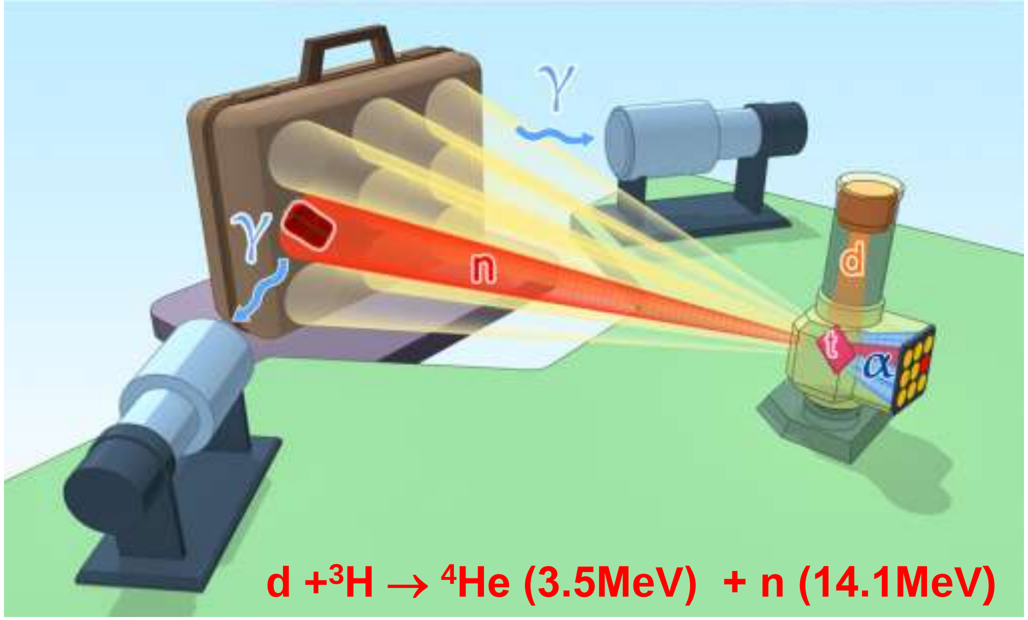
If we integrate over φ angle, it transforms into

$$W(\theta) \sim 1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)$$

Angular anisotropy of 4.44 MeV γ-line from the inelastic scattering of 14 MeV neutrons on carbon



Tagged Neutrons Method – TNM



Main components:

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

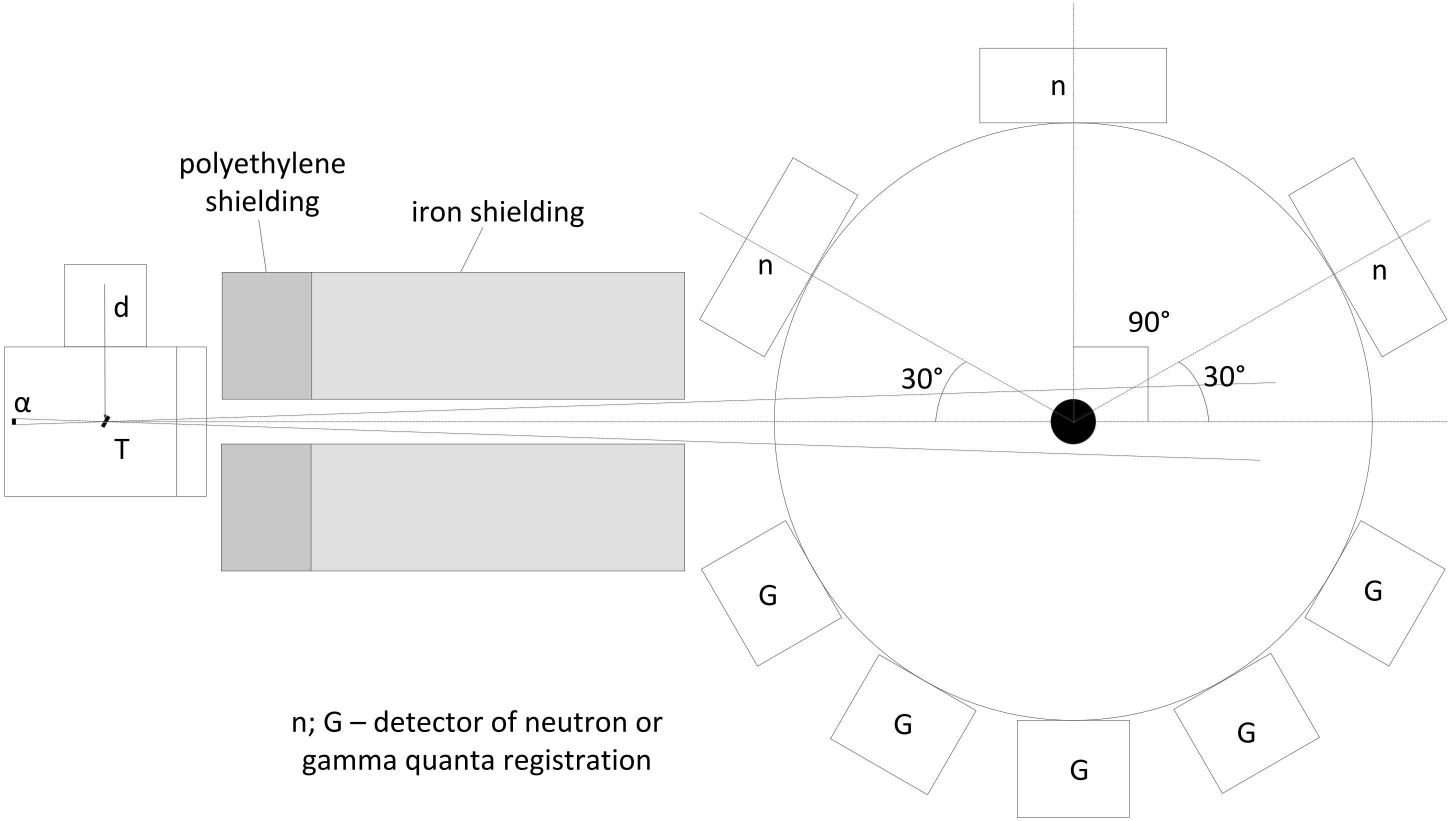
The method is successfully used for detection of hazardous substances

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

Schematic diagram of the experiments



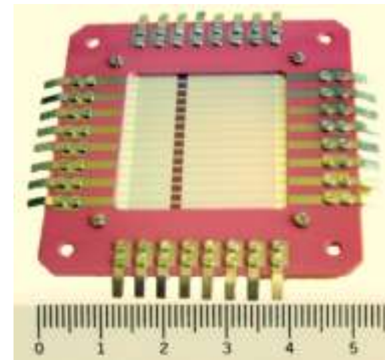
- **Neutron generator with built-in detector of α-particles**
- **Detectors of gamma-rays**
- **Detectors of neutrons**
- **Read-out electronics and data acquisition system**

Available

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

Required

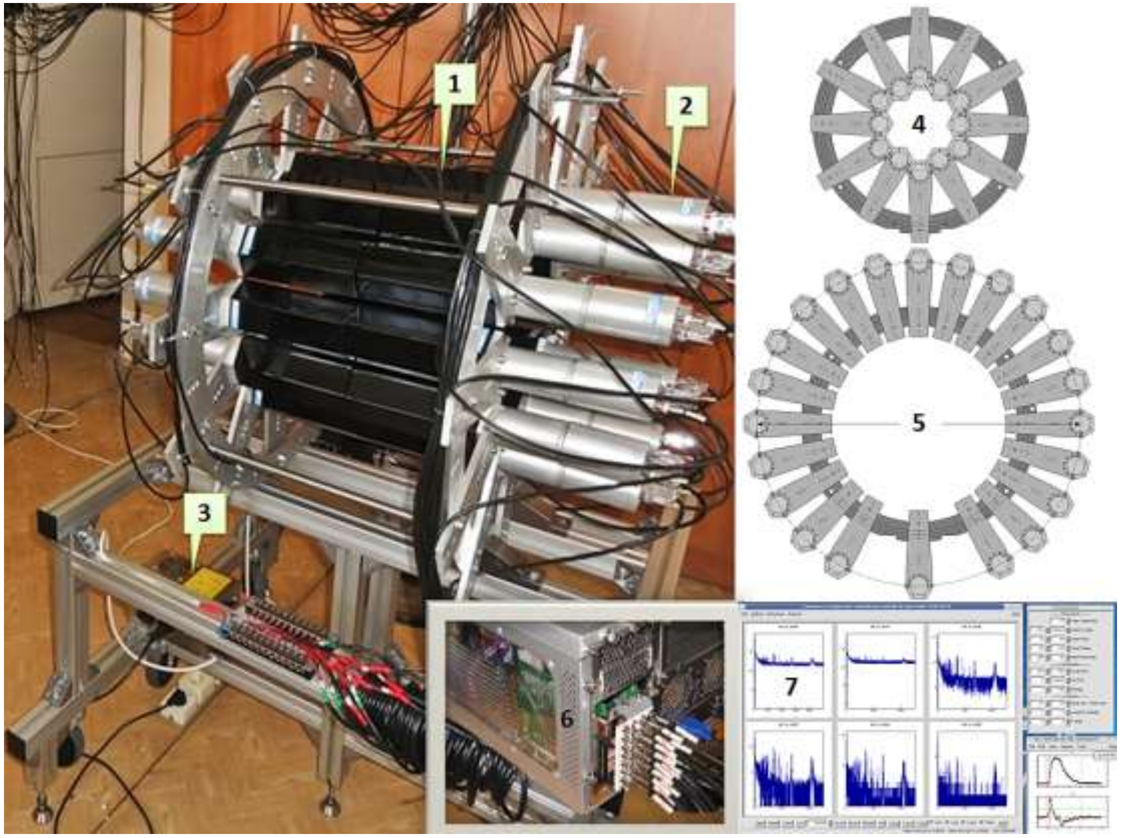
Neutron generator ING-27



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

Maximal intensity	**~5x10^{7} c^{-1}**
Neutron energy	**14.1 MэB**
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

Electronics and data acquisition

ADCM-16

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

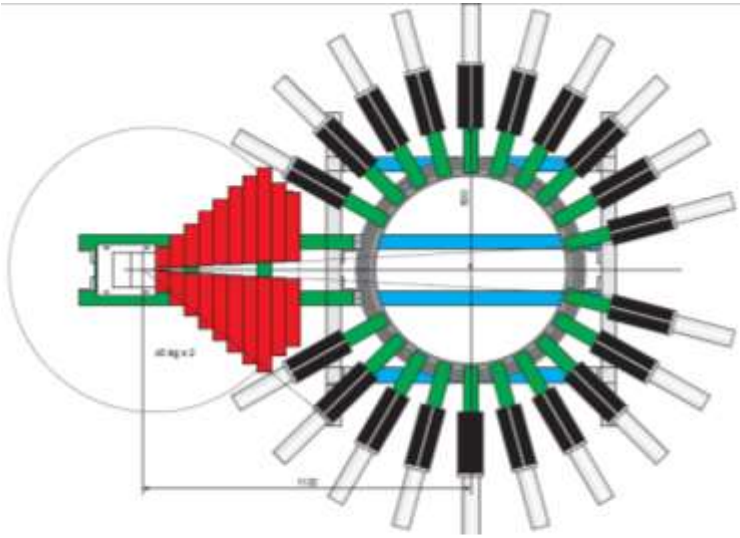
Sampling frequency 100 MHz

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

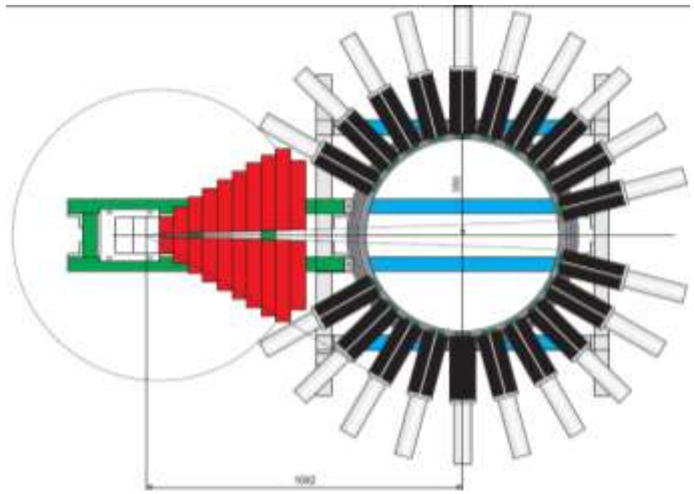
Maximum load of the system is ~ 10^5 events per second

Design of the geometrical arrangement and shielding

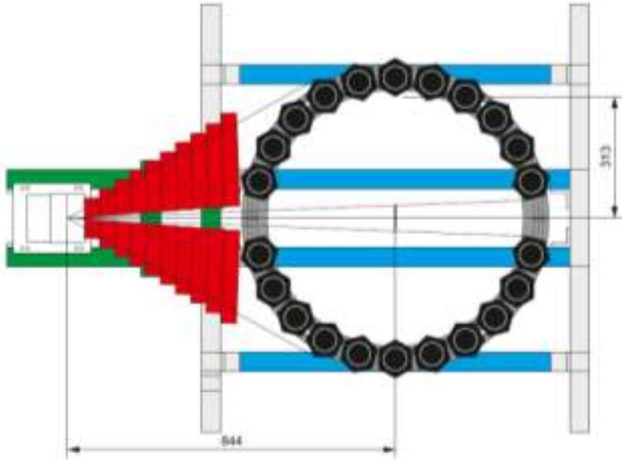
High resolution setup



Intermediate setup



High efficiency setup



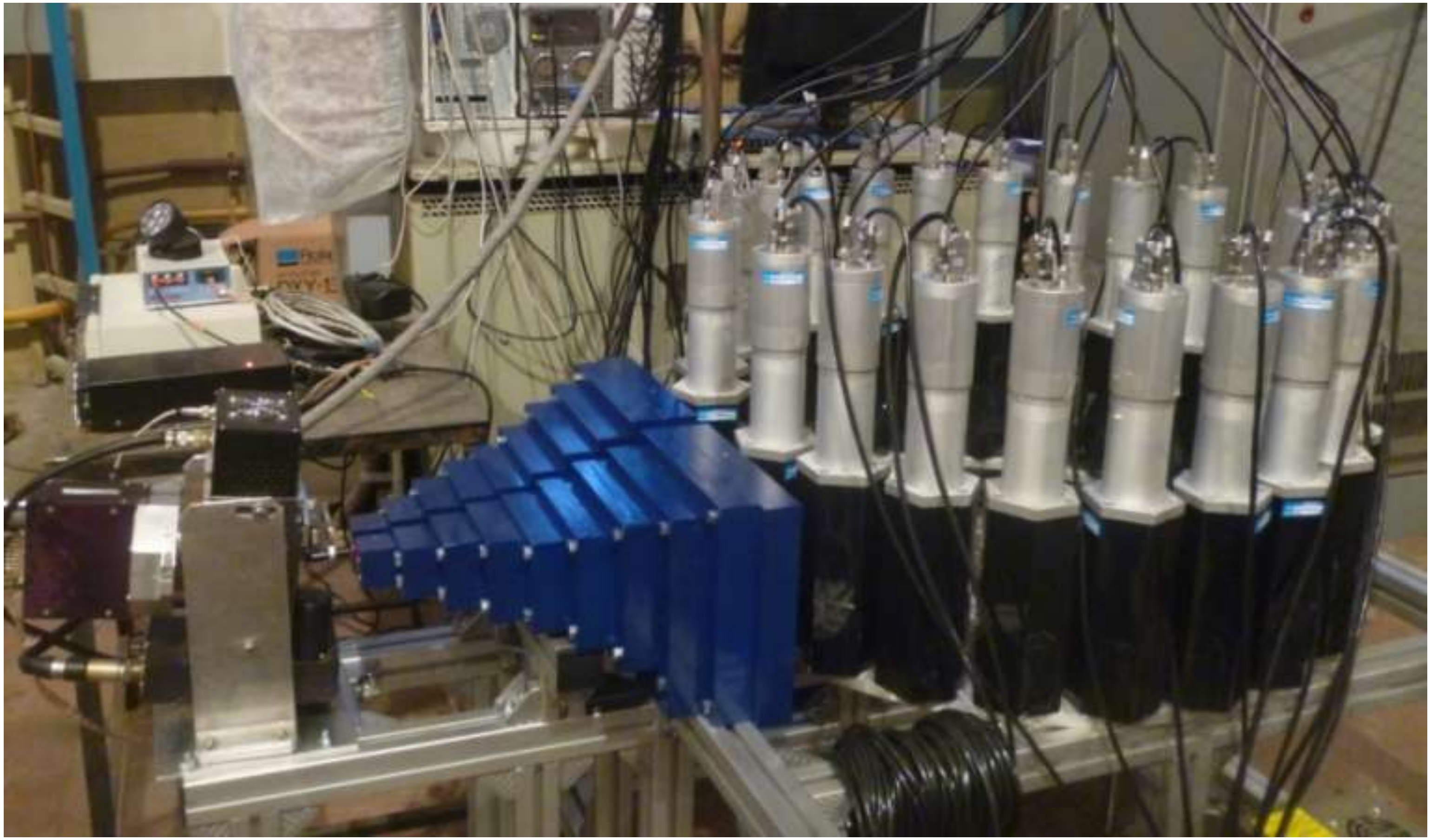
22 NaI(Tl) arranged <u>vertically</u>

Distance from the source to the target: ≈ 85cm

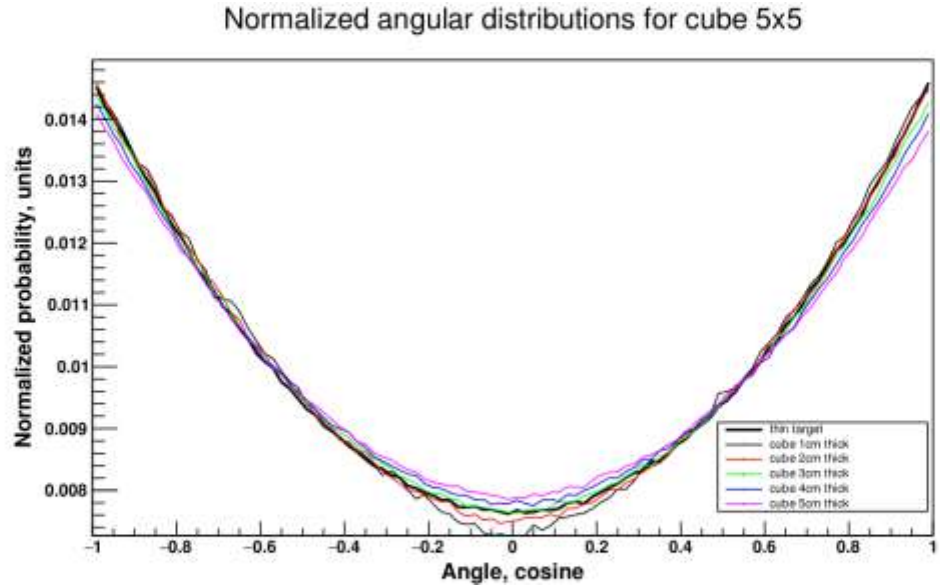
Distance from the target to the detectors: ≈ 32cm

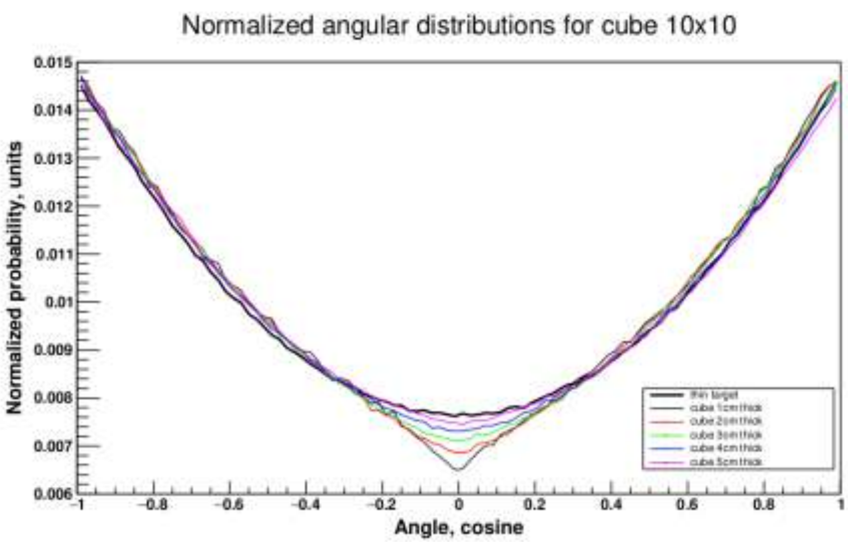
Detector shielding: 40cm of iron.

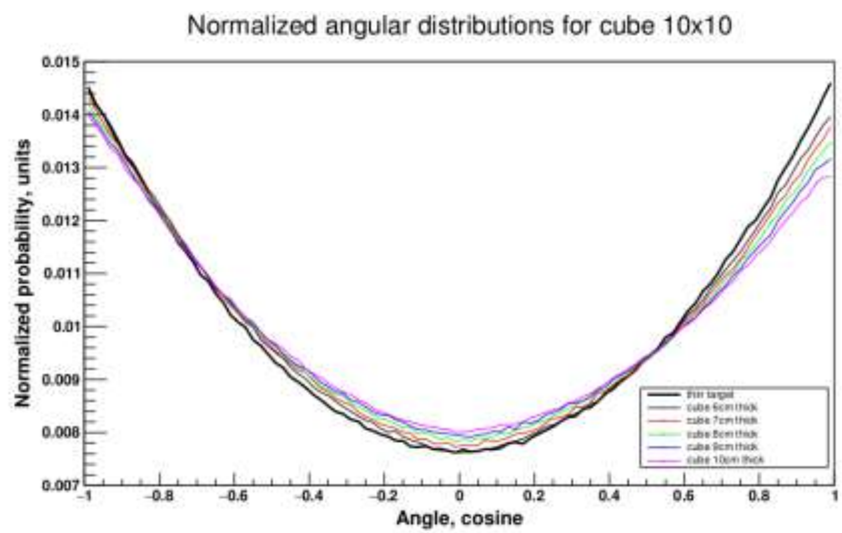
Design of the geometrical arrangement and shielding



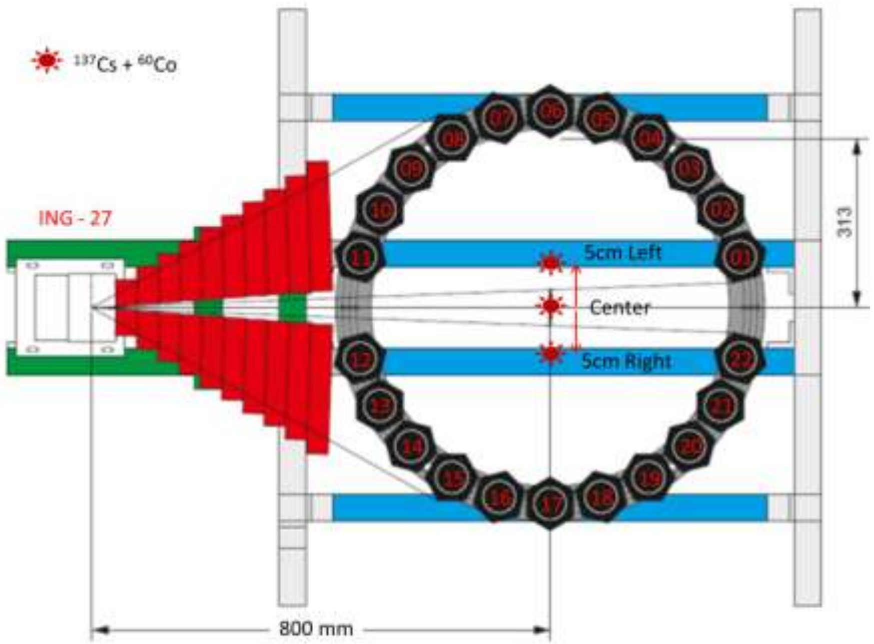
Optimization of the target size: Monte Carlo simulations using GEANT4 code

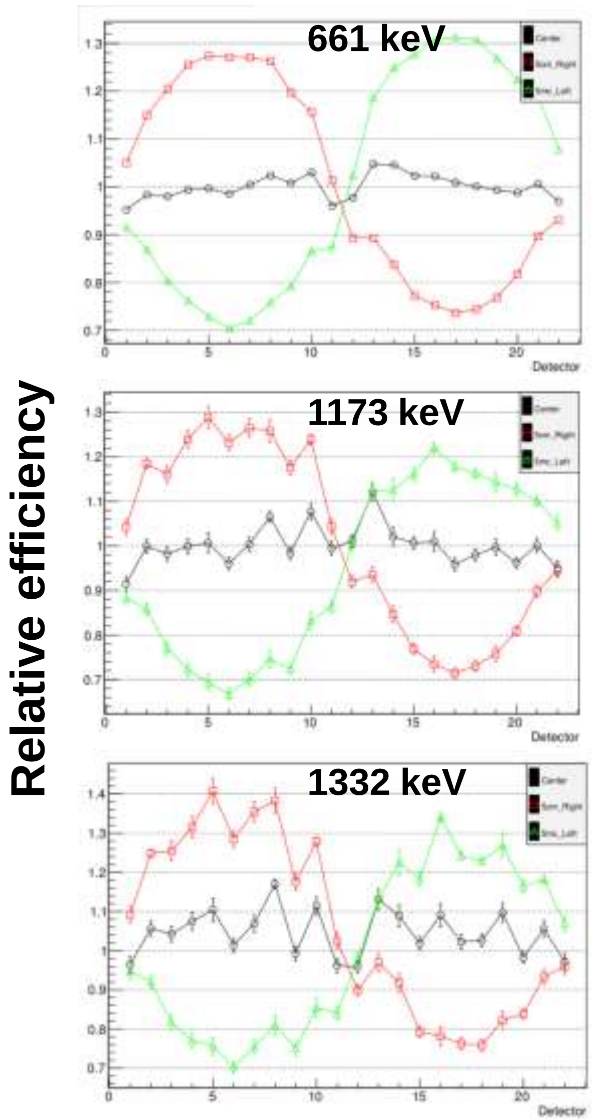




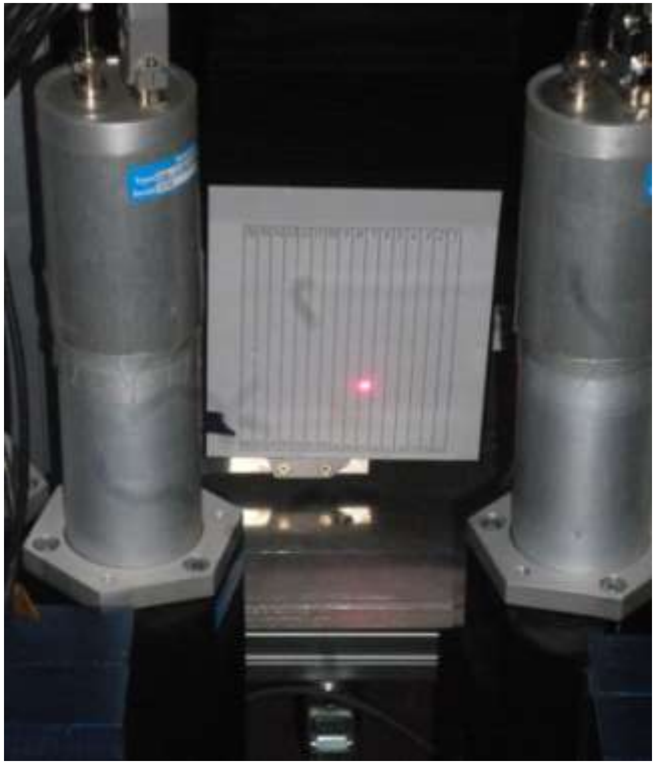


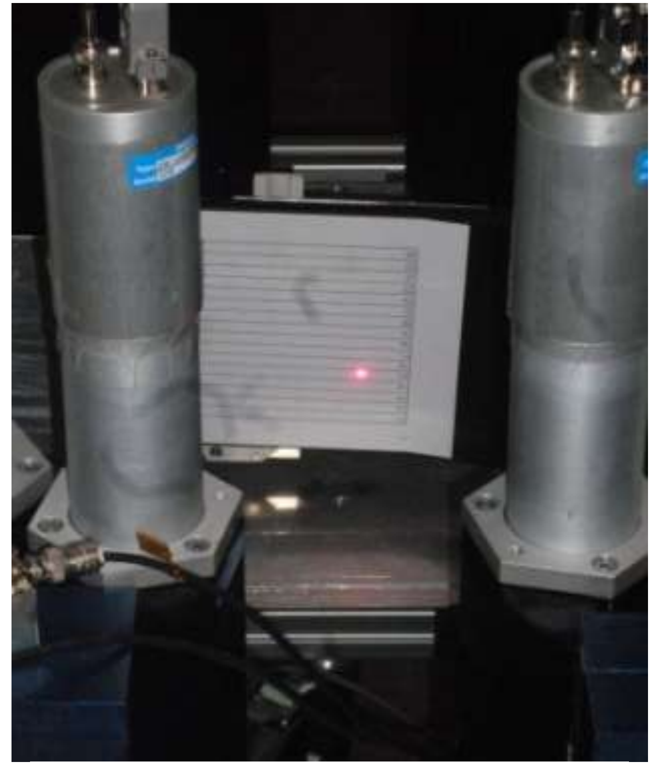
Efficiency calibration

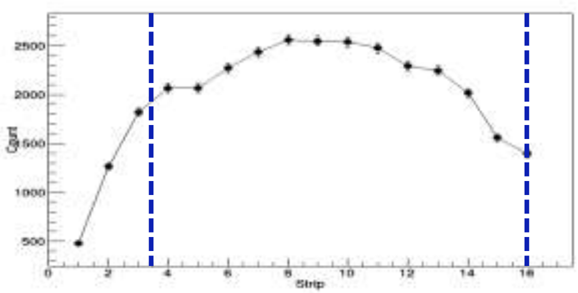


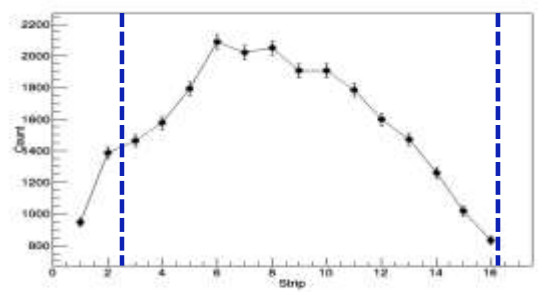


Beam profile measurements

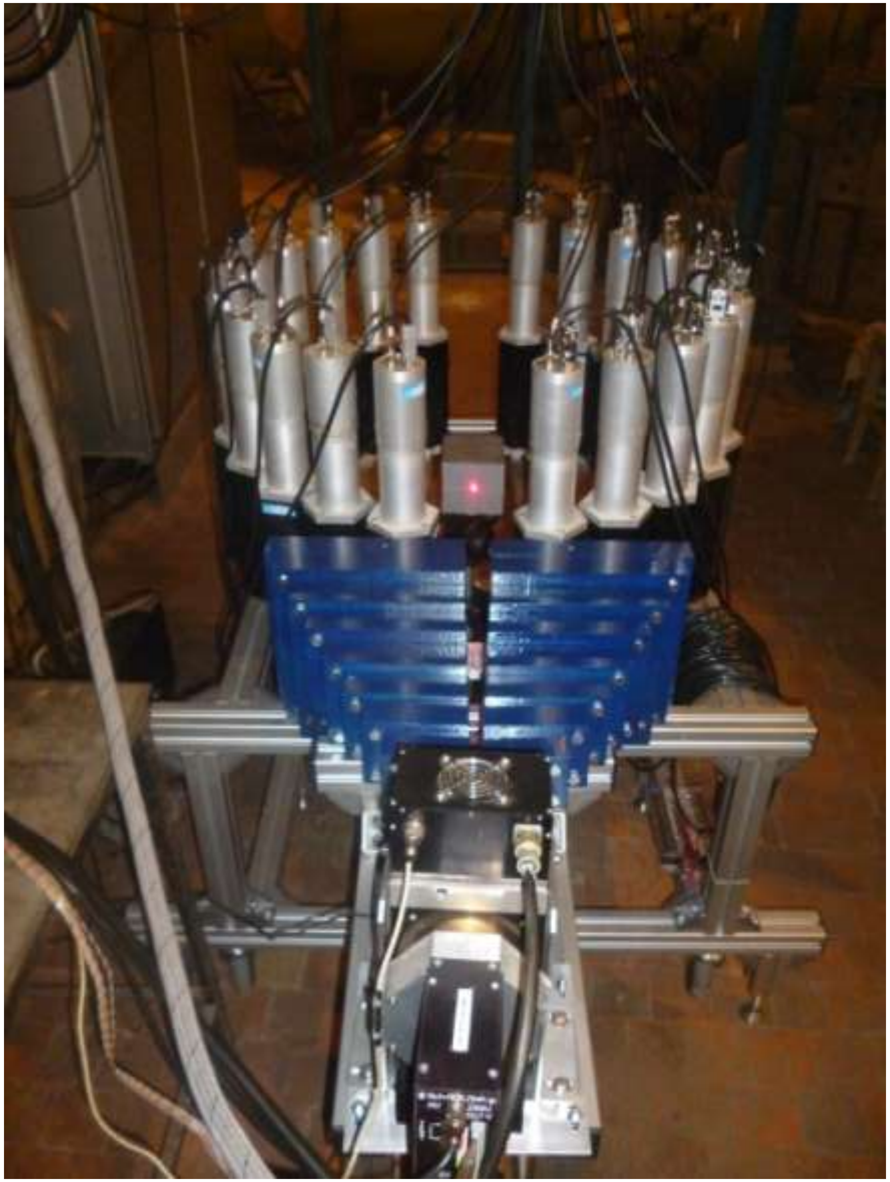








Production run

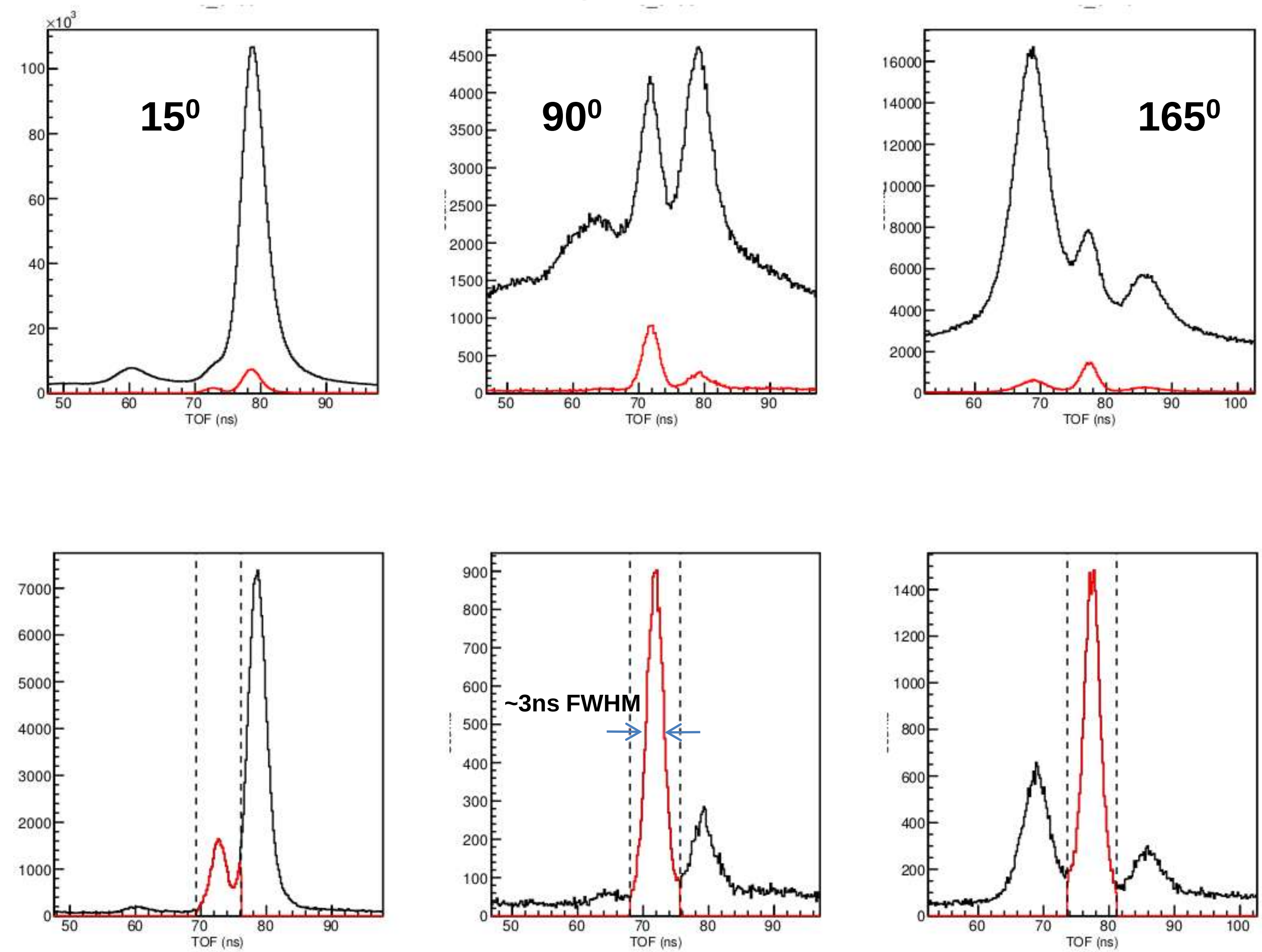


~ 8 hours of irradiation with 10x10x5cm graphite as a target

Time-of-Flight Spectra

All events

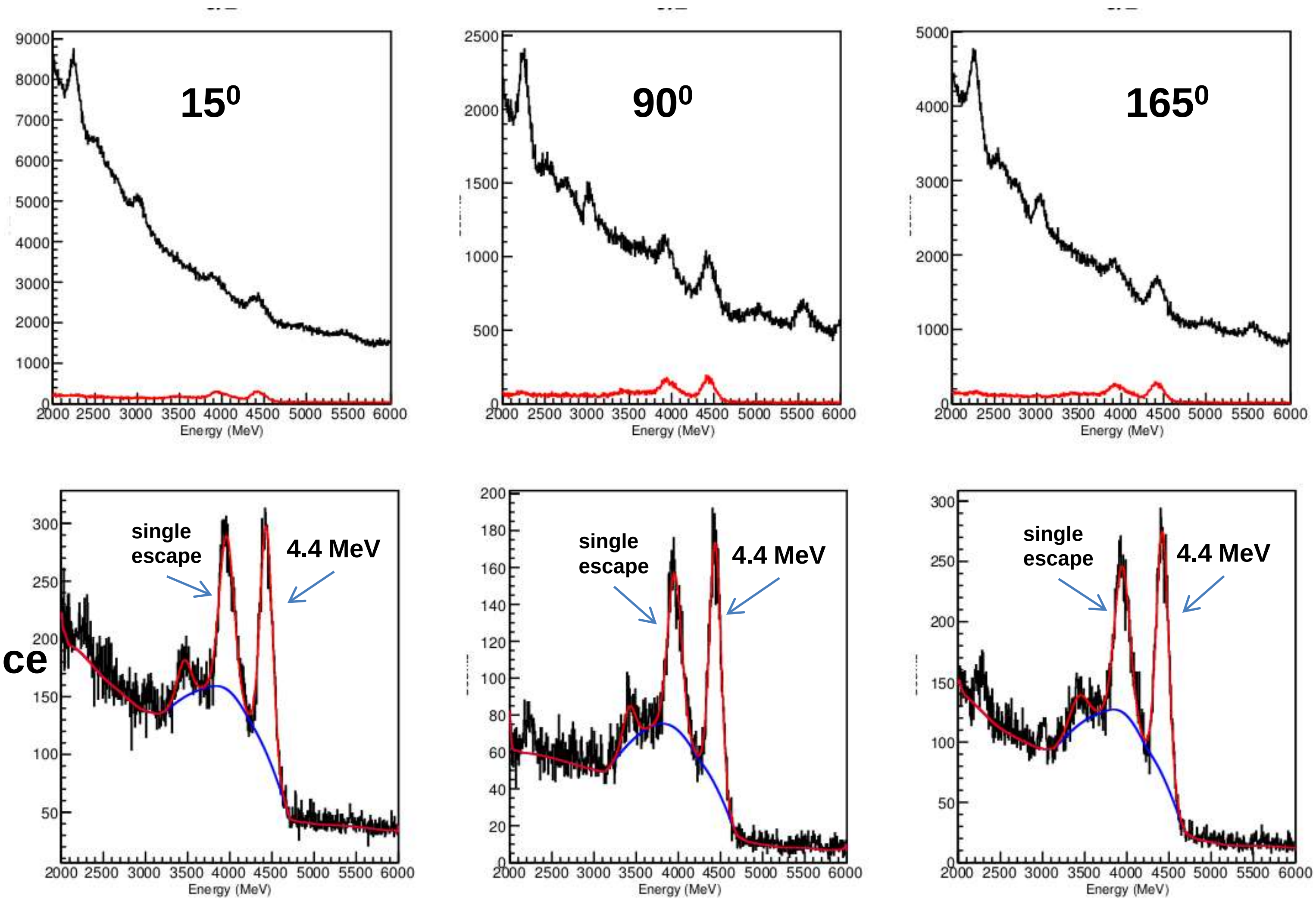
High threshold
(Eγ ~ 4 MeV)



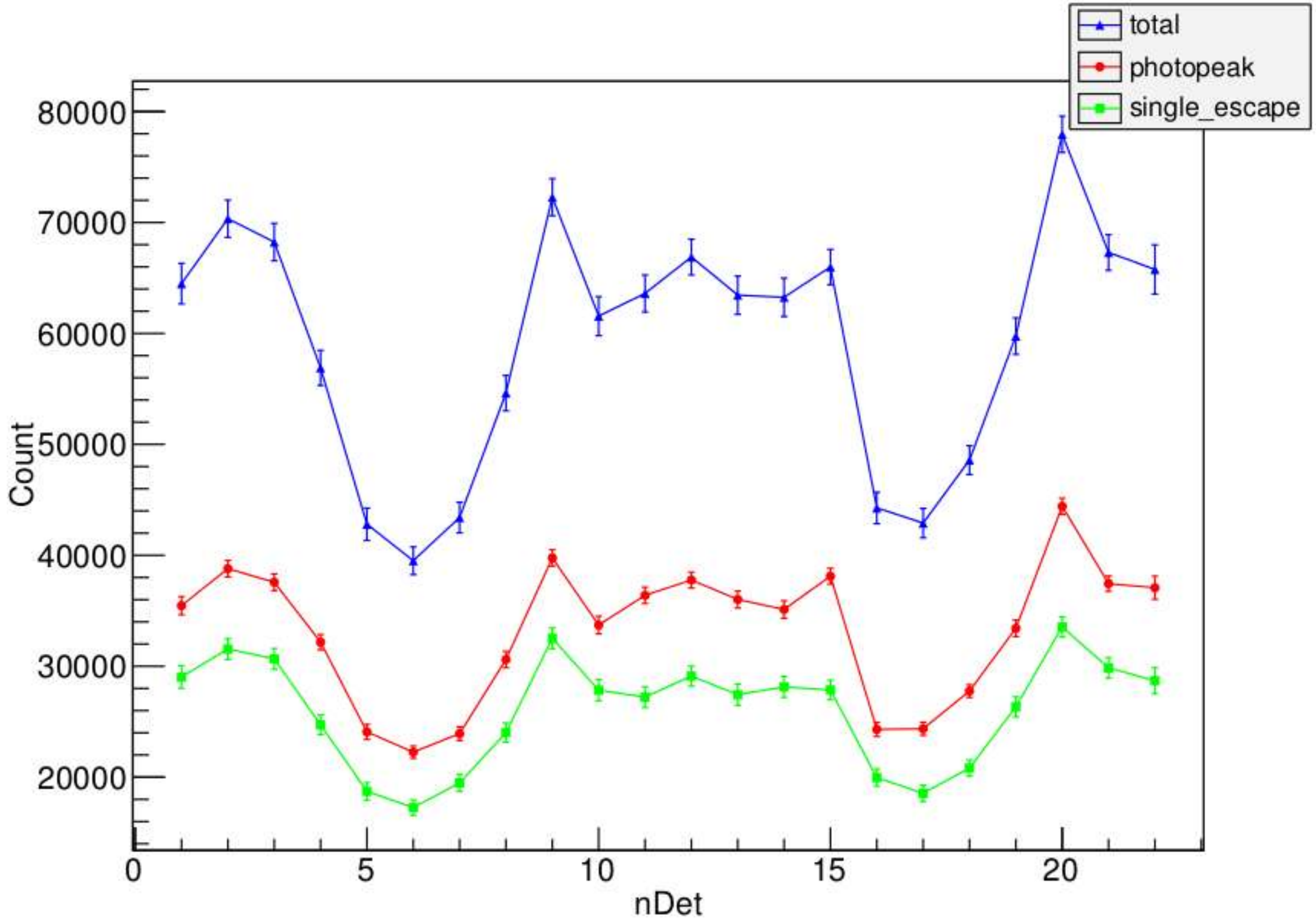
Energy Spectra

All events

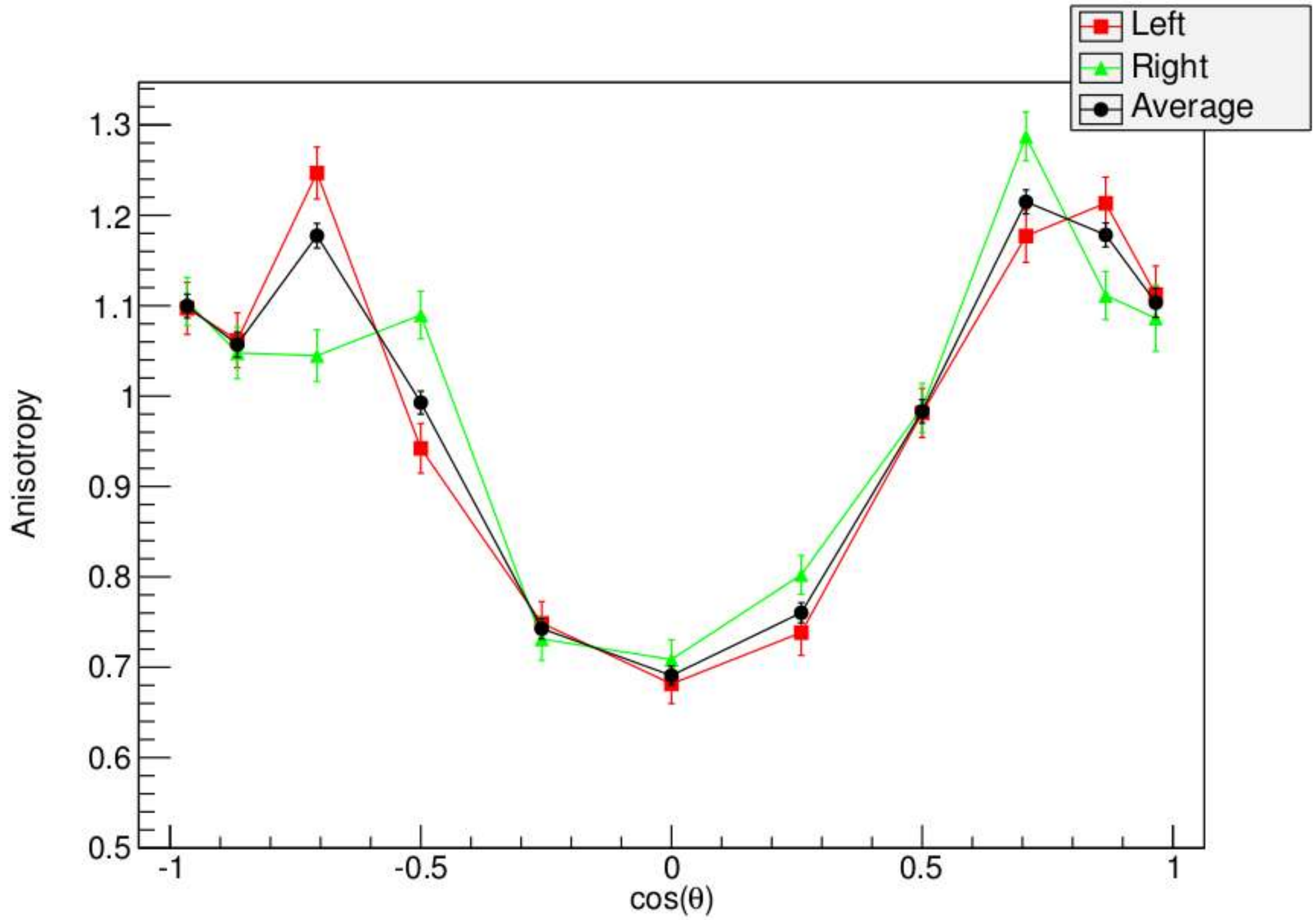
α-γ coincidence



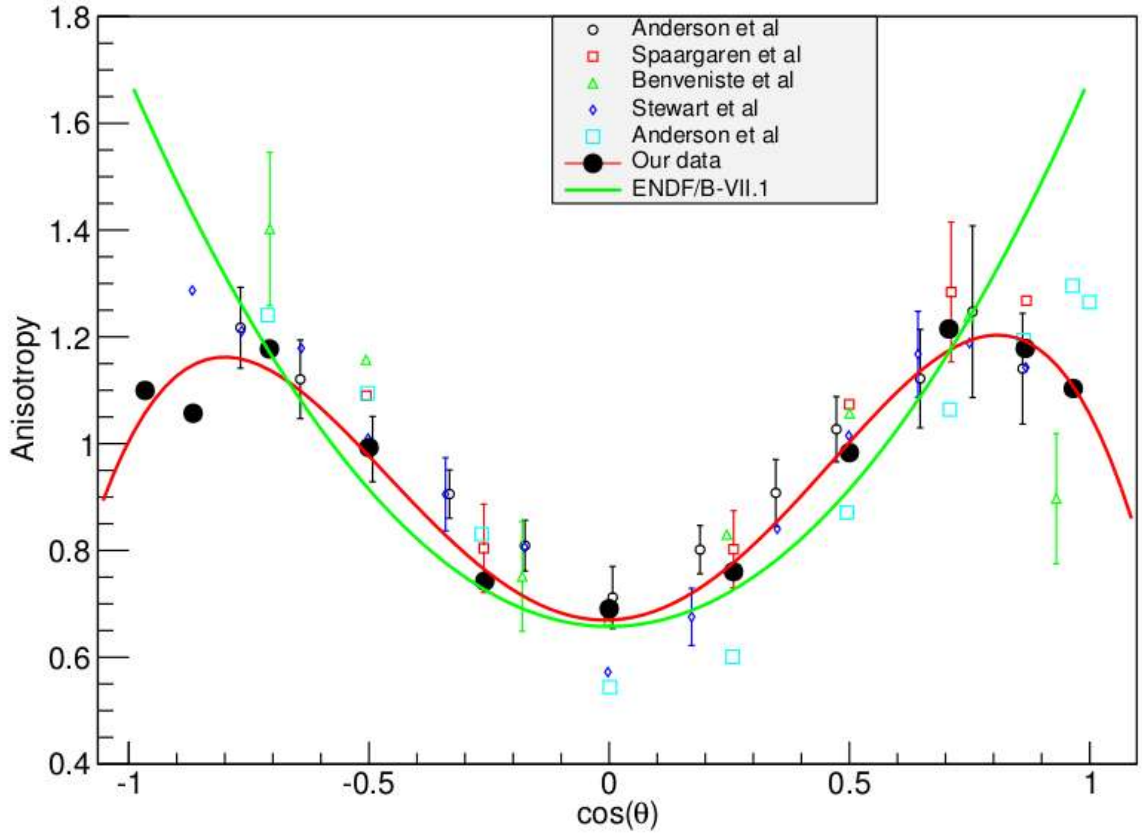
4.44 MeV gamma-ray yield as a function of the detector number



4.44 MeV gamma-ray yield as a function of cos(θ)



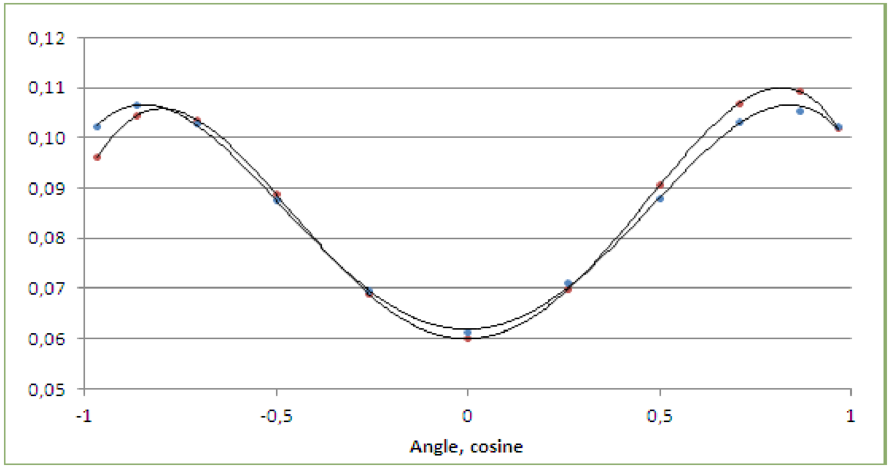
Results & comparison with other data



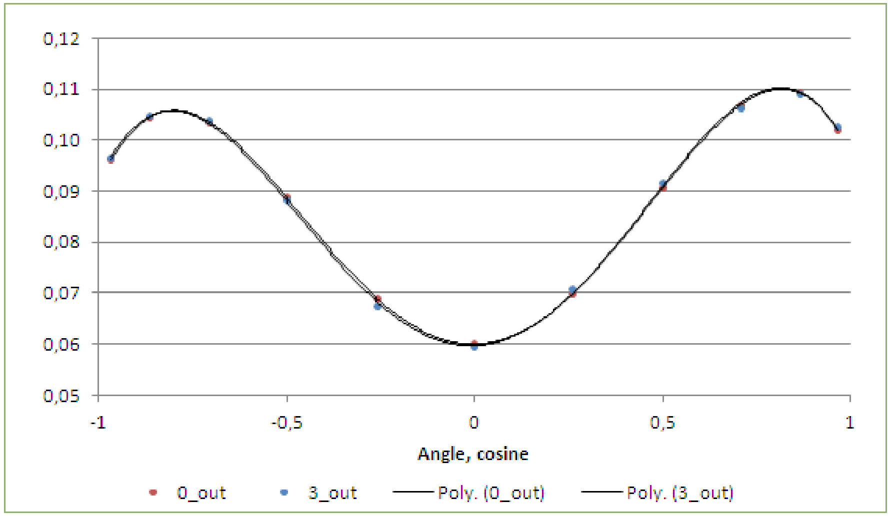
$$w \sim 1 + a \cdot \cos^2\theta - b \cdot \cos^4\theta$$

a=1.58±0.04
b=1.22 ±0.05

Geometrical corrections using GEANT4 with user defined anisotropy



- Experimental data fitted with a 4th order polinomial
- Angular distribution, calculated by GEANT4 using real experimental geometry and experimental angular distribution as input



Experimental and calculated anisotropies after the 3rd iteration ($\delta<10^{-2}$)

Final Legendre coefficients:

a2 = 7.83288E-02
a4 = -4.16003E-02

Conclusions & outlook

- Angular distribution of 4.44 MeV gamma-rays from the 1^{st} excited state of ^{12}C in the n,n'γ reaction has been measured with a good accuracy using the tagged neutron method.
- The data are mostly consistent with previous measurements.
- The evaluated parameters of the anisotropy from the ENDF/B and JENDL libraries do not include 4^{th} order coefficients which leads to a deviation at 0 and 180 angles.

- We're planning to measure/evaluate the elastically and inelastically scattered neutron angular distributions (differential cross sections), as well as the n'-γ angular correlations.
- Angular correlations in the inelastic scattering of 14 MeV neutrons on other nuclei, as well as in other reactions (e.g., n,2n) are to be investigated.

Thank you

for your attention