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

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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
In general case, the angular distribution is described by:

\[ W(\theta, \phi) = \sum_v P_v \sum_{m,m'} \alpha_m(v) \alpha_{m'}(v) X_{2m} \cdot X_{2m'} , \]

Where
- \( \theta, \phi \) - polar and azimuthal angle of the gamma emission;
- \( P_v \) - probability that mode \( v \) is formed;
- \( \alpha_m(v) \) – amplitude of the corresponding \( m \)-component;
- \( X_{2m} \) – normalized spherical harmonic.

If we integrate over \( \phi \) 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 $\alpha$-particles

• Detectors of $\gamma$-rays / neutrons

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

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 $\alpha$-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
Schematic diagram of the experiments

- Neutron generator with built-in detector of $\alpha$-particles
- Detectors of gamma-rays
- Detectors of neutrons
- Read-out electronics and data acquisition system
- Targets
- Shielding

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Neutron generator ING-27

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

Maximal intensity: \(~5\times10^7\ \text{c}^{-1}\)
Neutron energy: 14.1 M\(\text{eV}\)
Neutron radiation mode: steady-state
Power supply: 200\(\pm\)5 V
Maximum power consumption: 40 W
Dimensions: 130x279x227 mm
Weight: 8 kg
Operation time: \(~800\ \text{hours}\)

Detector of \(\alpha\)-particles: 9-pixel or 64-pixel position sensitive silicon detector

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24 NaI (TI) 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 vertically

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

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Efficiency calibration

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Beam profile measurements
Production run

~ 8 hours of irradiation with 10x10x5cm graphite as a target
Time-of-Flight Spectra

All events

15°

90°

165°

High threshold
($E_\gamma \sim 4$ MeV)

~3ns FWHM
Energy Spectra

All events

$\alpha$-\(\gamma\) coincidence

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4.44 MeV gamma-ray yield as a function of the detector number
4.44 MeV gamma-ray yield as a function of $\cos(\theta)$
Results & comparison with other data

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

\[ a = 1.58 \pm 0.04 \]
\[ b = 1.22 \pm 0.05 \]
Geometrical corrections using GEANT4 with user defined anisotropy

- Experimental data fitted with a 4th order polynomial

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:

- $a_2 = 7.83288E-02$
- $a_4 = -4.16003E-02$
Conclusions & outlook

• Angular distribution of 4.44 MeV gamma-rays from the 1\textsuperscript{st} excited state of $^{12}$C in the $n,n'\gamma$ 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\textsuperscript{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’-\gamma 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