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TANGRA – an experimental setup for basic and applied nuclear research by means of 14.1 MeV neutrons

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Abstract. For investigation of the basic characteristics of 14.1 MeV neutron induced nuclear reactions on a number of important isotopes for nuclear science and engineering, a new experimental setup TANGRA has been constructed at the Frank Laboratory of Neutron Physics of the Joint Institute for Nuclear Research in Dubna. For testing its performance, the angular distribution of γ-rays (and neutrons) from the inelastic scattering of 14.1 MeV neutrons on high-purity carbon was measured and the angular anisotropy of γ-rays from the reaction ^{12}C(n, n$'\gamma$)^{12}C was determined. This reaction is important from fundamental (differential cross-sections) and practical (non-destructive elemental analysis of materials containing carbon) point of view. The preliminary results for the anisotropy of the γ-ray emission from the inelastic scattering of 14.1- MeV neutrons on carbon are compared with already published literature data. A detailed data analysis for determining the correlations between inelastic scattered neutron and γ-ray emission will be published elsewhere.

1. Introduction

Nowadays, there is a need of high-quality neutron-nuclear reaction data in almost all the branches and fields of human society activities such as: basic physics and astrophysics (testing theoretical models, designing experiments, analyzing experimental data, origin of chemical elements); nuclear fusion and fission power reactors (nuclear fuel cycle, operation safety, radiation shielding, waste disposal and transmutation); nuclear medicine (radioisotope production, dose calculation, radiotherapy diagnostics); homeland security (device R&D, stockpile stewardship, criticality safety, nuclear forensics, detecting illicit trafficking of nuclear materials); industrial applications (elemental analysis) and life sciences. The main neutron induced reaction characteristics such as: total and differential cross-sections; mass, energy, angular, yield and multiplicity distributions of reaction products are object of permanent theoretical and experimental investigations to determine them with better accuracy. Particularly, there is an absence of new and precise experimental data on the interaction of fast neutrons with energy of about 14 MeV with a number of important elements for nuclear sciences such as Li, Be, B, C, N, O, etc.

With existing powerful computing possibility now scientists have the opportunity for enhancing nuclear data programs.

For investigation of the basic characteristics of 14.1- MeV “tagged” neutron induced nuclear reactions, a new experimental setup TANGRA has been constructed at the Frank Laboratory of Neutron Physics of the Joint Institute for Nuclear Research in Dubna [1].

2. Experimental setup

The TANGRA (**Ta**gged **N**eutrons & **G**amma-**Ra**ys) setup is a multi-purpose, multifunctional, multi-detector, mobile setup, designed for studying the characteristics of the products (characteristic γ-rays and neutrons) in a number of nuclear reactions induced by “tagged” neutrons with energies of 14.1 MeV.

In the configuration shown in Fig. 1 it consists of: a portable generator ING-27 (1) [2], 40 cm-thick iron shield (2) [3], 22 NaI(Tl)-based γ-detectors arranged in the shape of a “Daisy”-flower (“Romashka” in Russian) (3), a computerized system for controlling the ING-27 operation, acquisition/analysis of signals from it and a detector array.

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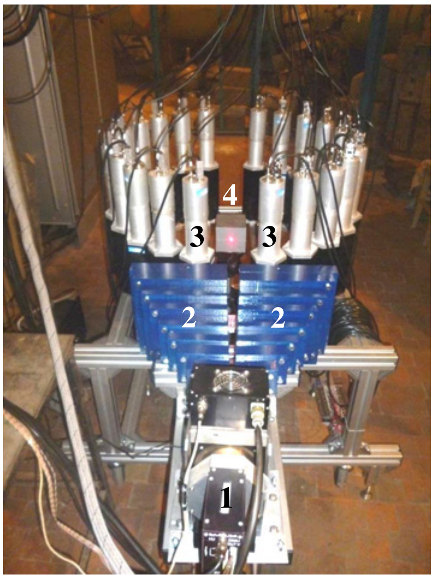

Figure 1. A photo of the "source-detector" part of the TANGRA experimental setup: 1 – neutron source (ING-27), 2 – iron shield-collimator of neutrons and γ-rays, 3 – NaI(Tl) scintillation detectors of γ-rays and neutrons, 4 – carbon (^{12}C) test target-sample.

This configuration can be used for the investigation of (double) differential cross sections of (in)elastic scattering, capture and/or fission reactions, induced by 14.1 MeV "tagged" neutrons on a number of important isotopes for nuclear science, the multiplicity of the reaction products, their angular distributions and possible correlations between them.

2.1. Neutron generator

The ING-27 is a sealed-tube portable generator of 14.1 MeV neutrons, which are producing in the D-T fusion-fission reaction ^{2}H(^{3}H,^{1}n)^{4}He (Q = 17.6 MeV, $E_\alpha = 3.52$ MeV, $E_n = 14.1$ MeV).

In the ING-27 vacuum tube, at a distance of 62 mm from the center of the titanium-tritium (TiT) target, a double-sided silicon (Si) strip α-particle detector is positioned. The mutually perpendicular strips form an 8 × 8-matrix with a size of each element (pixel) of 4 × 4 mm^2. Thus, the overall sensitive area of this 64-pixel α-detector is 32 × 32 mm^2. The signals from the stripes are fed to the corresponding charge-sensitive preamplifiers via a 16-pin connector. The ING-27 is operated remotely by PC Windows OS.

Because of the reaction kinematics, the α-particles and neutrons are irradiated nearly in opposite direction (the inclination angle is about 8°). This way, by registering the α-particles one can "tag" (and hopefully count) the corresponding neutrons.

The spatial characteristics of the 64 "tagged" neutron beams were measured with a n-profile-meter containing 16 plastic scintillation strips. The dimension of a single strip is 150 × 7.5 × 5 mm^3. The intensity distribution of a "tagged" neutron beam on the plane $\{x,y\}$, perpendicular to the direction of its propagation z, obtained from the coincidences between the signals from the n-profile-meter's vertical strips and those from a single α-particle detector pixel (x-profile), can be deduced from Fig. 2.

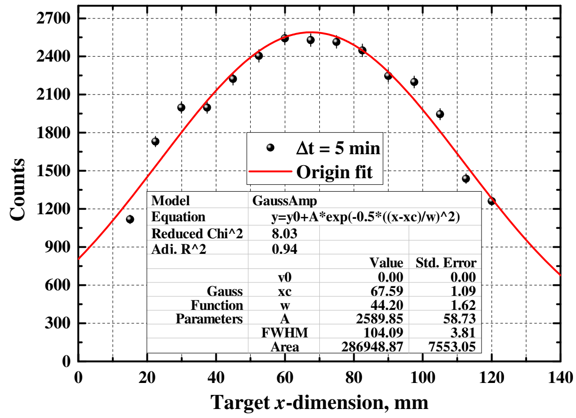

Figure 2. The x-profile of a "tagged" neutron beam.

2.2. "Romashka" gamma-ray detector system

As detectors of γ-rays we used 22 NaI(Tl) regular hexagonal prism crystals (apothem: 42.5 mm, height: 200 mm). They were placed vertically on a horizontal circular ring from aluminum with a radius of ≈370 mm, the whole array resembles the form of "Romashka"-flower. This configuration has a higher geometrical efficiency compared to that of the horizontally disposed probes. The azimuthal angle between the central axes of the adjacent NaI(Tl) detectors is 15°.

The data acquisition system is a 32-channel signal digitizer, which consists of 2 × 16-channel, 14-bit, 100 MHz, ADCM-16 boards with signal processing core, coupled with CCB-PCIe carrier board [4]. Maximum load of the system is ∼10^5 Hz. The software package includes drivers for the PCI-interface, programs for running the electronics, recording in list-mode the waveforms from the α- and γ-detectors, subsequent determination of signals' time- and amplitude- characteristics and creating their distributions.

The average energy resolution of the γ-ray detectors, at current disposition and configuration, is ∼8.5% for the 662 keV γ-line of ^{137}Cs, which is ∼20% higher than in noise-free laboratory environment. The $\gamma\gamma$-coincidence timing resolution $(FWHM)_{\gamma\gamma}$ for the "fast-slow" NE213-NaI(Tl) γ-detector system, using a standard point γ-ray source of ^{60}Co (1173 keV, 1332 keV), was found to be ∼1.8 ns (Fig. 3).

The ability to separate the contributions of neutrons and γ-rays to the total load of the spectrometry system, via their different time-of-flight of ∼35–40 cm distance, was investigated by two NaI(Tl) probes and a ^{252}Cf n-γ source.

The number of correlated $\gamma\gamma$- and γn- events as a function of the delayed-time is shown in Fig. 4. The $\gamma\gamma$- and γn- coincidence timing resolutions of the NaI(Tl)-NaI(Tl) detector system was found to be $(FWHM)_{\gamma\gamma} \sim$ 4.8 ns and $(FWHM)_{\gamma n} \sim$ 14 ns, correspondingly.

3. Anisotropy of γ-rays from ^{12}C(n,n′γ)^{12}C

For testing the TANGRA setup performance, the angular distribution of γ-rays (and neutrons) from the inelastic scattering of 14.1 MeV neutrons on high-purity carbon was

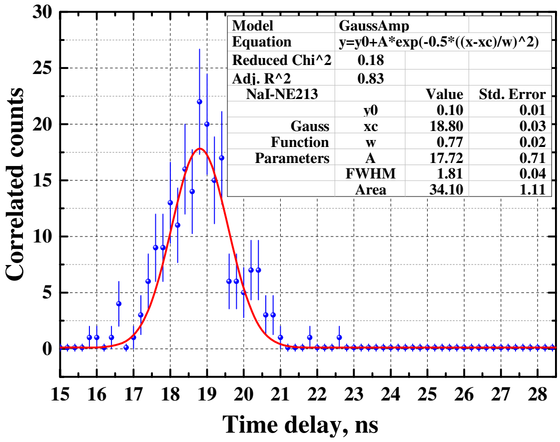

Figure 3. NE213-NaI(Tl) ^{60}Co $\gamma\gamma$-coincidence curve.

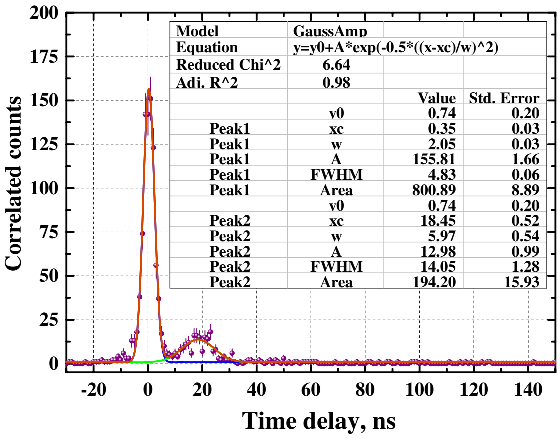

Figure 4. ^{252}Cf γ-rays and neutrons correlated time-of-flight.

measured and the angular anisotropy of γ-rays from the reaction ^{12}C(n,n$'\gamma$)^{12}C was determined.

This reaction is very important in fundamental [5] and applied nuclear physics for: measuring the (double) differential cross-sections [6], testing theoretical models, non-destructive elemental analysis of materials containing carbon, determining the release of energy to tissue or tissue-equivalent materials, radiation damage effects in reactor materials containing carbon, neutron transport calculations, understanding and quantitative description of neutron detectors or neutron dosimetry, etc. Data on the angular correlation between inelastically scattered nucleons and γ-rays are frequently used to determine whether this process involves a compound nucleus or a direct nuclear interaction mechanism. Usually, the angular distributions of the discrete γ-rays produced in the inelastic scattering of neutrons are expressed by the first three even terms of the Legendre polynomials expansion. In the past this reaction was widely investigated, but controversial results on the anisotropy of the γ-rays from the ^{12}C(n,n$'\gamma$)^{12}C-reaction were obtained by different groups of scientists [7–20], particularly, at small n'-scattering angles (Fig. 5).

Because of the importance of this reaction and the contradictory experimental results obtained till now, recently, we have started new measurements with the TANGRA-setup. For this purpose, a high-purity carbon parallelepiped with spatial dimension of $\approx 10 \times 10 \times 5\,\text{cm}^3$

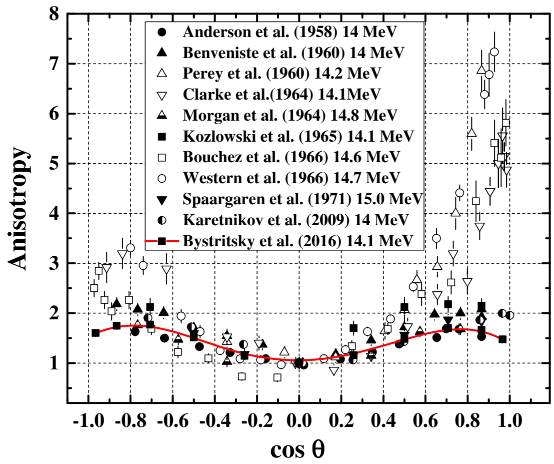

Figure 5. The anisotropy of the irradiation of γ-rays from the ^{12}C(n,n$'\gamma$)^{12}C-reaction as a function of cos θ.

was located in the center of the "Romashka"-system and the signals (waveforms) from all the 22 NaI(Tl) probes and the α-detector were recorded for 8 hours in list-mode. The distance from the source to the carbon-target was approximately 85 cm, that from the carbon-target to the detectors was $\approx$32 cm, the thickness of the iron shielding was $\approx$ 40 cm. The energy spectra of the γ-rays in corresponding ^{12}C(n,n'γ)^{12}C-reaction time-windows were analyzed and the area under the 4.4 MeV peaks were determined, taking into account all the components of the NaI(Tl) response function. The γ-ray emission anisotropy was calculated for the angles θ in the interval from 15° up to 165° with a step of 15°. The angular resolution was $\approx$4.4°.

The preliminary experimental results, normalized to the $\sigma(\theta = 90^\circ)$ are shown in Fig. 5 (full squares) together with the already published literature data [7–21]. The spline-function curve, drawn through the experimental points, is just for guiding the eyes.

4. Conclusions

For investigation of the basic characteristics of 14.1- MeV neutron induced nuclear reactions, a new experimental setup TANGRA has been constructed and tested. The tagged neutron method in combination with the NaI(Tl) "Romashka"-system allowed us to measure the angular distribution of 4.4 MeV γ-rays produced in the inelastic scattering of 14.1 MeV neutrons on ^{12}C nuclei by exciting its first (2^+) level. Within the limits of statistical errors, the calculated values for the anisotropy are found to be in good agreement with the results obtained in the first experiments [7,8].

In the evaluated library ENDF/B-VII.1 2$^{\text{nd}}$-order Legendre polynomial expansion is used to describe the ^{12}C(n,n'γ)^{12}C γ-rays angular distribution. This leads to a significant discrepancy between the proposed theoretical model and experimentally obtained angular distribution of 4.4 MeV γ-rays at azimuthal angles $135^\circ < \theta < 45^\circ$, as shown in Ref. [21].

A detailed data analysis for determining the correlations between the inelastic scattered neutrons and

γ-ray emission is ongoing and the results will be published elsewhere.

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