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THE FRANK LABARATORY OF NEUTRON PHYSICS

FINAL REPORT ON THE START PROGRAMME

Measurement of the neutron inelastic scattering cross section on ^{12}C using the TANGRA facility

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DECLARATION

I, **Utkarsha Mishra**, declare that the work presented in the project report titled **" Determination of the neutron inelastic scattering cross section on ^{12}C using the TANGRA facility"** is my original work from **February 11th to April 6th 2024** and has not been submitted elsewhere for academic credit or publication. It has been carried out by me under the guidance of **Prof. Yuri Kopatch**, at Joint Institute for Nuclear Research, Frank Laboratory of Neutron physics. I assert that all information and sources used in this project are accurately cited in the reference section, and I have given credit to all authors and contributors as appropriate. I declare that I have adhered to ethical guidelines while conducting this research project, and all participants provided informed consent before their involvement. I also declare that I have not plagiarized any content or data during the research process and have taken all necessary measures to ensure that this work is original and follows ethical standards.

I acknowledge and understand that any violation of these ethical guidelines could result in severe consequences, including academic penalties, legal action, and loss of professional reputation.

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Abstract

TANGRA is a flexible approach for exploring neutron-induced inelastic nuclear reactions at ~14.1 MeV energy. The experimental facility is located at FLNP (Frank Laboratory of Neutron Physics) JINR, Dubna, Russia. We produced neutrons via the d + t → α + n method. An alpha detector was utilized to identify the alpha particle and tag the neutron. For this reason, it is referred to as the tagged neutron facility. The material is irradiated with these fast neutrons, and the unique gamma from inelastic neutron scattering is recorded during the time interval between neutron emission and gamma quanta. It will help us to understand the fundamentals of neutron-induced nuclear reaction physics. In this report, we employed $^{12}C(n, n\ \gamma)$ to determine the angular distribution by using the fast neutron scattering with an energy 14.1MeV.

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1. INTRODUCTION

The TANGRA (Tagged Neutrons and Gamma Rays) facility is the fascinating facility to study neutron-induced nuclear reactions. It consists of multiple detectors, such as alpha detectors and gamma detectors. For generation of fast neutron around 14.1 MeV at here used fusion-fission reaction between the deuterium *d* with tritium ^{3}H ($d + {}^{3}H \rightarrow \alpha + n$). When a deuterium beam of 100 KeV interacts with the tritium target, it will decay into alpha particles and neutrons. At this point, the neutron and α-particle go in opposing directions at an angle of 180˚. It is feasible to calculate the direction and escape time of the fly neutron by recording the α-particle with alpha detector that travels with it. This mechanism is known as tagged neutron method. An alpha particle with an energy of 3.5 MeV and a neutron with an energy of 14.1 MeV are produced in this process. 17.59 MeV of energy emerges as a result of the reaction. The generator produces regular fluency of 14.1 MeV neutrons at a rate of 5×10^{7} per second. This fast neutron has several uses for investigation through sample irradiation, including inelastic neutron scattering to identify the composition of materials [1,2] for full volumes and cross-section measurement to explore nuclear reaction processes. When fast neutron interacts with the material it will excite the nuclei of material. Because of the excitation of nuclei, it produces the characteristic gamma rays, which are detected by the gamma detector with the coincidence of alpha particles, and it then becomes stable. When fast neutron interacts with the material it will excite the nuclei of material. Because of the excitation of nuclei, it produces the characteristic gamma rays, which are detected by the gamma detector with the coincidence of alpha particles, and it then becomes stable.

Detected gamma may be used to study for angular distribution of gamma quanta [3]. It is important in the inelastic scattering process because it offers information about the nature of the neutron-nucleus interaction and permits the mechanism to be determined, either compound nucleus reaction or direct reaction. Inelastic scattering of fast neutrons typically results in significantly smaller cross sections than thermal neutron capture events [6].

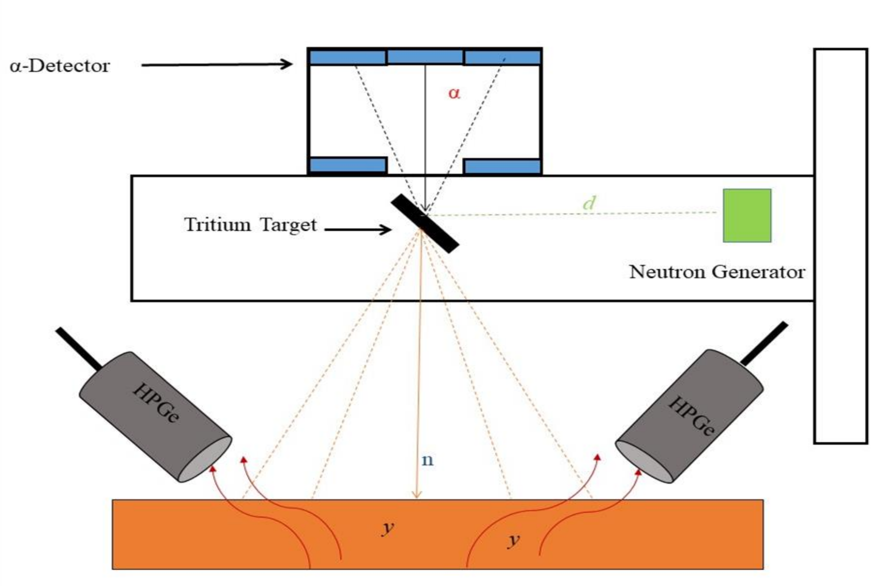

Fig.1 Layout of tagged neutron method [4].

One exception is the cross sections for fast neutron inelastic scattering on light materials. When surveying oil wells using neutron logging, heavy elements like Cl, S, Cu, K, Na, Ni, and Ti are captured by thermal neutrons, while C, O, Al, Fe, P, Mg, and Si are best determined by inelastic scattering of fast neutrons [9]. The primary advantage of a tagged neutron setup is that it offers information on the time of flight of gamma quanta. This allows for selecting the proper gamma ray based on the time of light and solely identifying emitted γ quanta. From the region of the object being studied. Irradiating an object with both aluminium and hydrogen nuclei is the simplest case.

Inelastic neutron scattering excites 27Al nuclei, resulting in the emission of gamma quanta with energies of 844, 1015, 2211, and 3004 keV[7]. Hydrogen captures thermal neutrons, forming gamma quanta with an energy of 2233 keV. In the 2211-keV peak region of aluminium, gamma quanta from hydrogen capture are present [8]. The number of events in the peak determines the aluminium concentration, which is affected by the humidity of the object material. The elemental content of ore samples can be determined without any sample preparation. It takes 10-15 minutes to determine the elemental composition of big samples (up to 10 kg) and granularity (up to 300 mm) in field circumstances. Several examples exist of thermal neutron capture lines superimposed on fast neutron inelastic scattering lines. The tagged neutron approach distinguishes between noise and valuable signals by taking into account interactions with thermal neutrons and gamma quanta arrival times.

Knowing the neutron flux and its profiles with high precision is critical for the absolute measurement of neutron-induced reaction cross sections. The number of registered alpha particles from the DT-fusion reaction can be utilized to monitor neutrons emitted by the TiT neutron generating target. Monitoring precision is determined by the alpha-sensor's detecting efficiency as well as the quantity of lost (absorbed, dispersed) alpha-particles before they reach the sensitive area. We use the n-profilometer to accurately place the target under inquiry such that as many tagged beams as possible hit it and detectors surround it. An example of two-dimensional mapping of ING-27 tagged neutron beams, one of their profiles, and the experimental technique with beams' azimuthal projections.

2.Experimental facility

2.1 TANGRA Setup

TNM (Tagged Neutron Method) has been investigated since its first observed reaction in 1948. This approach is also known as Associated Particle Imaging API. The monograph provides detailed information on the initial TNM experiments using Van de Graff accelerators. TNM experiments began in 1999 at the Joint Institute for Nuclear Research (JINR) with the assembly of a 4-section alpha-particle detector at the Van de Graff accelerator at the Laboratory of Neutron Physics (LNP).

A basic TNM setup consists of three components: a neutron source with an alpha-particle detector, gamma-ray detectors for characteristic radiation, and data acquisition electronics. The setup may include biological shielding based on the operating conditions. TNM was further enhanced with the arrival of a portable neutron generator, created at the All-Russian Scientific Research Institute of Automation (VNIIA, Moscow) by order of JINR. The LNP's Van de Graff accelerator was in a six-meter tower, but the portable generator was barely 30 cm in size and only 8 kg. This enabled the device to be used in several experimental settings. Portable generator technology has advanced, allowing for higher intensities of up to $2 \times 10^8 s^{-1}$, upto 256 tagged beams, and longer generator lifetimes.

Fig.2 Experimental Hall of TANGRA at FLNP, JINR.

2.2 ING-27 (Neutron Generator)

The "Dukhov VNIIA" firm manufactures the ING-27 portable neutron generator, which generates 14.1 MeV neutrons. The portable neutron generator features a sealed tube and built-in alpha detector. Alpha-particle detectors are typically built of silicon. However, gallium arsenide detectors are also being developed.

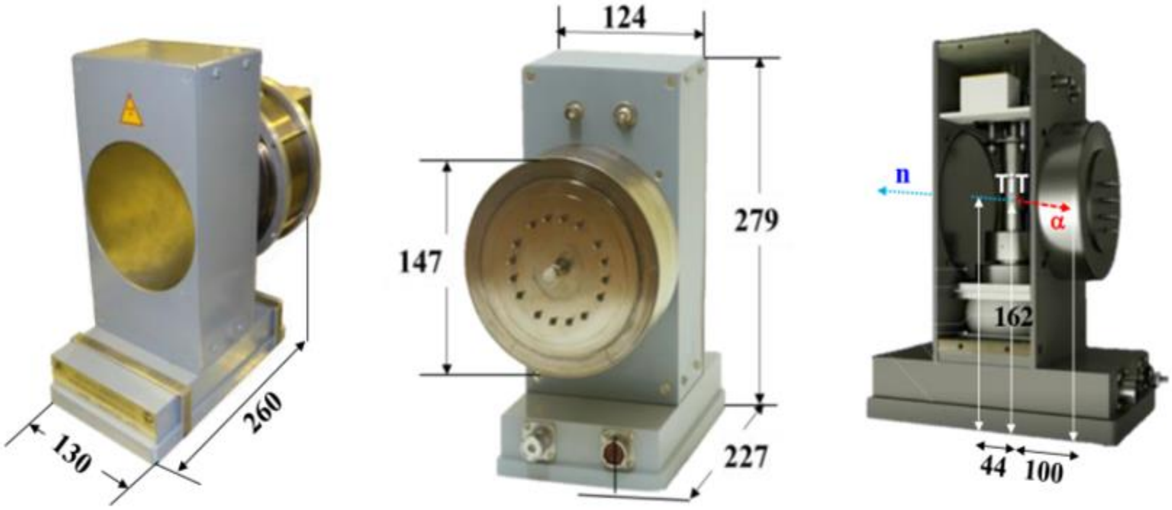

Fig.3 ING-27 dimensions (mm) and the direction of irradiation of DT-reaction fragments.

Alpha-particle detectors are distinguished by their granularity and pixel size. The generator generates a continuous neutron flux at an intensity of $5\times10^8 s^{-1}$. The neutron generator's power consumption is 40 W. The generator has a lifetime of 800 hours. The silicon alpha-detector features a 3 × 3 matrix with 10 × 10 mm pixels. The strip is the sum of vertical and horizontal pixels.

The pixel size of an alpha particle detector determines the size of the tagged neutron beam. Assuming the spot size of the deuteron beam on the target is lower than the pixel size, the size of the neutron beam at a distance L from the NG target (Tritium) can be calculated using simple geometric considerations:

$$D = d\,\frac{L}{\iota},$$

Where, d is the pixel size of the alpha-particle detector and ι is the distance between the detector and the tritium target.

The α-γ coincidence system's time resolution determines the spatial size of the region along the neutron momentum vector. The setup can determine an elementary volume, known as a voxel, indicating the material's elemental composition.

The spatial size S of the region perpendicular to the neutron momentum vector depends on the size D of the tagged beam and the number n of pixels in the alpha-particle detector.

$$S = n\,D.$$

The α-γ coincidence system's time resolution determines the spatial size of the region along the neutron momentum vector. Typical temporal resolution values range from 2-4 ns. At a neutron speed of 5 cm/ns, the distance in the direction of the neutron momentum is around 10-20 cm.

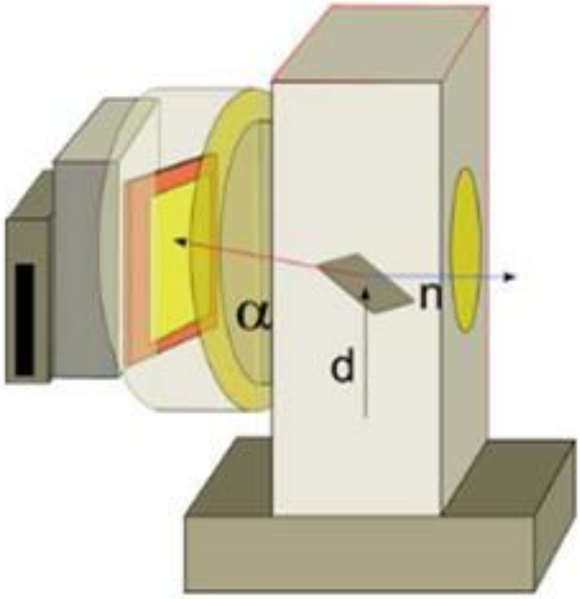

Fig.4 ING-27 Neutron Generator

2.3 HPGe Detector

We employed two gamma detectors based on HPGe crystal to measure y quanta caused by irradiation of the sample (^{12}C) by a fast-tagged neutron. Our experiment utilized an ORTEC GMX30-83-PL-S high-purity germanium (HPGe) detector. HPGe1 had a crystal diameter of 65.9 mm and a length of 84.8 mm, while HPGe2 had a crystal diameter of 69 mm and a length of 72.4mm. Quality gamma spectrometry uses detectors built of exceedingly pure germanium. The spectrometer utilizes a semiconductor HPGe detector. Such detectors offer an ideal cost-to-quality ratio and have proven to be effective when utilized in rapid neutron applications. The total energy resolution of the detector system was 55 Fe (710 eV) at the 5.9 keV line. The (α-γ)-coincidence system's average time resolution across all γ-detectors was AMP. The (α-γ)-coincidence system had an average time resolution of AMP 6Micros across all γ-detectors. A lead collimator reduced background from direct neutrons and protected the detector from fast neutron damage. For this experiment, we must calibrate our detectors using the gamma quanta source. We calibrated the detector using a radioactive gamma source. Here, we employed ^{60}Co, ^{137}Cs, ^{22}Na, and ^{152}Eu.

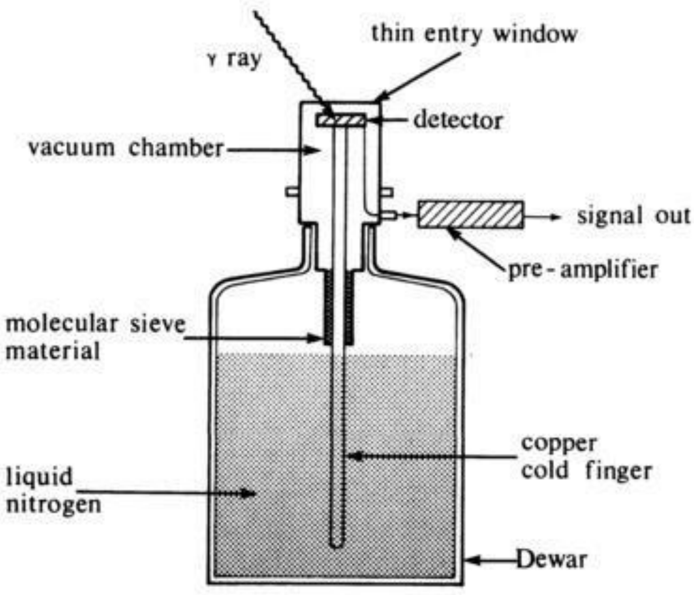

Fig.5 Fundamental layout of HPGe Detector

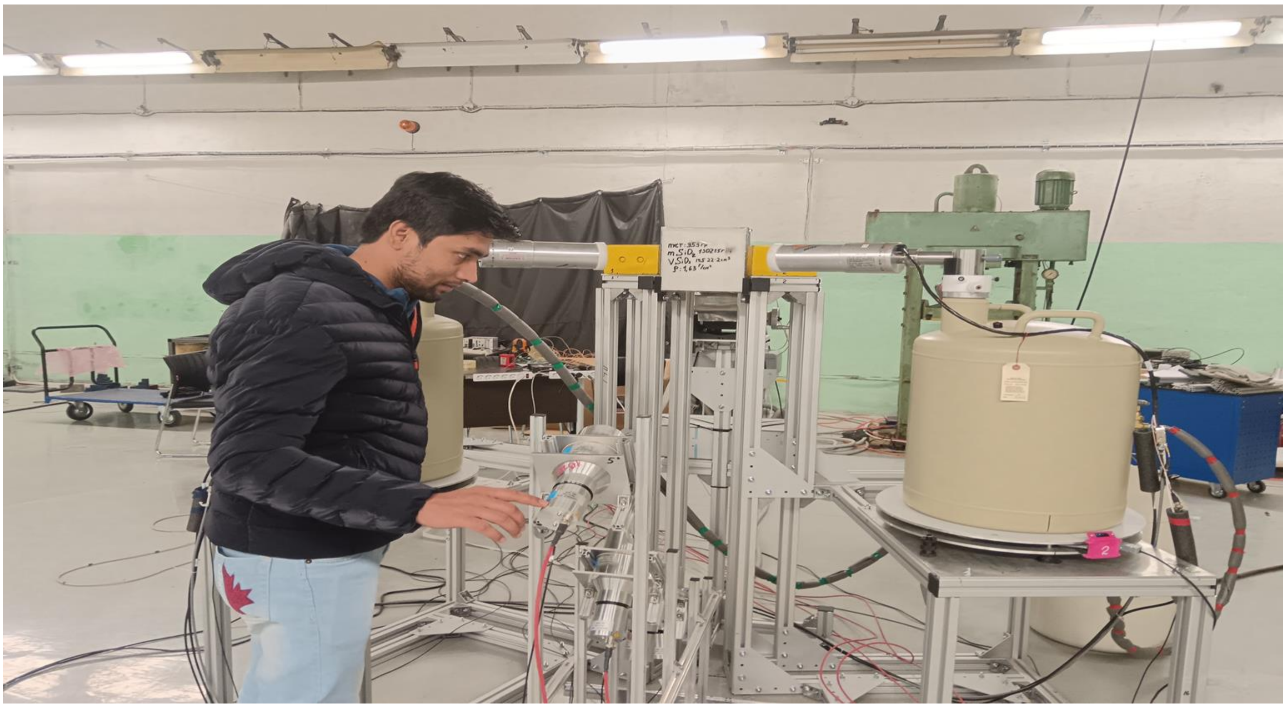

Fig.6 Experimental setup of TANGRA-HPGe.

2.4 Data Acquisition System (DAQ)

We used fully digital data acquisition systems (digitizers) in the tagged neutron experiments. These systems consist of analog-to-digital converters clocked by a single clock generator, allowing us to receive and store measured voltage values in intermediate memory with time reference (time stamp). The control circuits read the accumulated pulse waveforms and execute mathematical computations before sending them to a computer via a serial port.

We use one computerized data collection 32-channel ADC systems, Alpatov's Digital Signal Recorder DSR-32, to capture amplitude signals from pixelized alpha-sensor, γ-detector systems, and n-profilometers (Fig. 5). All HPGe gamma spectrometer studies were conducted using the DSR system [10,11]. The digitized amplitude signals (waveforms) are stored in list-mode (one-by-one) on the computer hard disk for offline analysis by user-created C++ programs or CERN ROOT scripts.

32-channel, 200 MHz, 11-bit digitizer, USB-3 connection; ~105 events/s for each input channel. This DAQ can work also with the HPGe detector.

Fig.7 Digital Signal Recorder DSR-32.

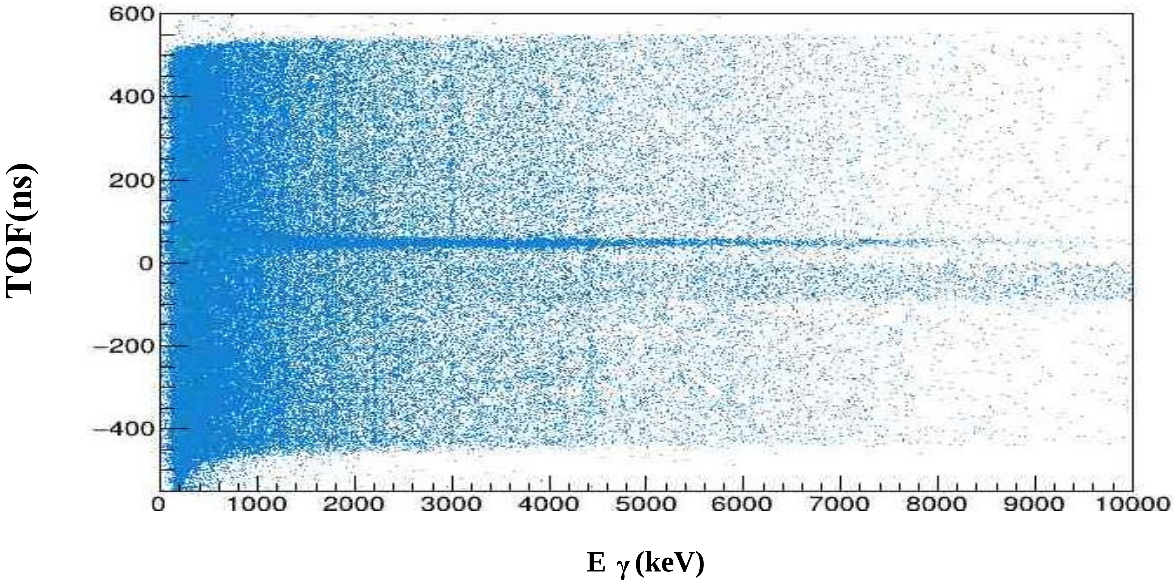

Fig. 8 Two Dimensions histogram of gamma coincidence with alpha. This figure 6 depicts the raw data spectrum from the MCA (multichannel analyser). We obtained this spectrum data from HPGe utilizing the data acquisition system.

3.Measurement Technique

3.1 Target Details

We conducted our experiments at the Tangra Experimental Hall, FLNP, JINR, Dubna, Russia. We used ^{nat}C with roughly 99% of ^{12}C purity for irradiation with fast neutrons from the tagged neutron facility at 14.1 MeV. The target dimensions are 20×20×2 cm^3 (l×b×h) and in form of solid pellet. Because of the irradiation, it will excite the carbon isotopes (^{12}C), and it will transition to the excited state and become stable by producing gamma quanta. In this experiment, we intense to measure the inelastic neutron cross-section for the ^{12}C. So we measured the gamma quanta energy of ^{12}C, and the reaction is described below.

$$n(14.1keV) + {}^{nat}C \longrightarrow {}^{12}C + \gamma\text{-ray (charterstics)}$$

3.2 Data Analysis

The gamma ray of an element is measured by produced an interaction between a neutron and the element with a neutron energy of 14.1 MeV. This induction is significant for nuclear data, neutron activation analysis, and element composition analysis. The most useful measurement tool is HPGe. This detector allows us to register closely lying levels that other detectors, such as scintillation, cannot perform due to their energy resolution.

We employed two HPGe detectors with an energy resolution of 2.3 keV for cobalt (^{60}Co) to measure the gamma quanta of ^{12}C. Using these gamma quanta, we can determine ^{12}C's inelastic neutron cross section.

The HPGe detector's charge collection characteristics affect the energy released in the detection medium, depending on the time resolution.

Two-dimensional time spectra are required to select a single time window for the whole energy range, while one-dimensional time spectra alone are insufficient. **Fig.8** illustrates a two-dimensional energy-time spectrum with specified time frames.

We extracted data for analysis from HPGe detectors using a data acquisition system designed for studying two-dimensional time amplitude spectra with an alpha-gamma coincidence window. Count inside the coincidence window for reactions caused by tagged neutrons in the sample, and outside the window for background counts caused by untagged neutrons interacting with the sample's surroundings. To accurately measure neutron inelastic scattering, we must subtract the background count window from the alpha-gamma coincidence window. To estimate energy-dependent time windows, we partition two-dimensional spectra into small energy segments (typically 100-300 keV), create time-of-flight projections, then approximate the resulting time spectra in energy windows using Gaussians and substrate. The major peak, known as the coincidence peak, is caused by neutron interactions between the sample and nearby experimental elements.

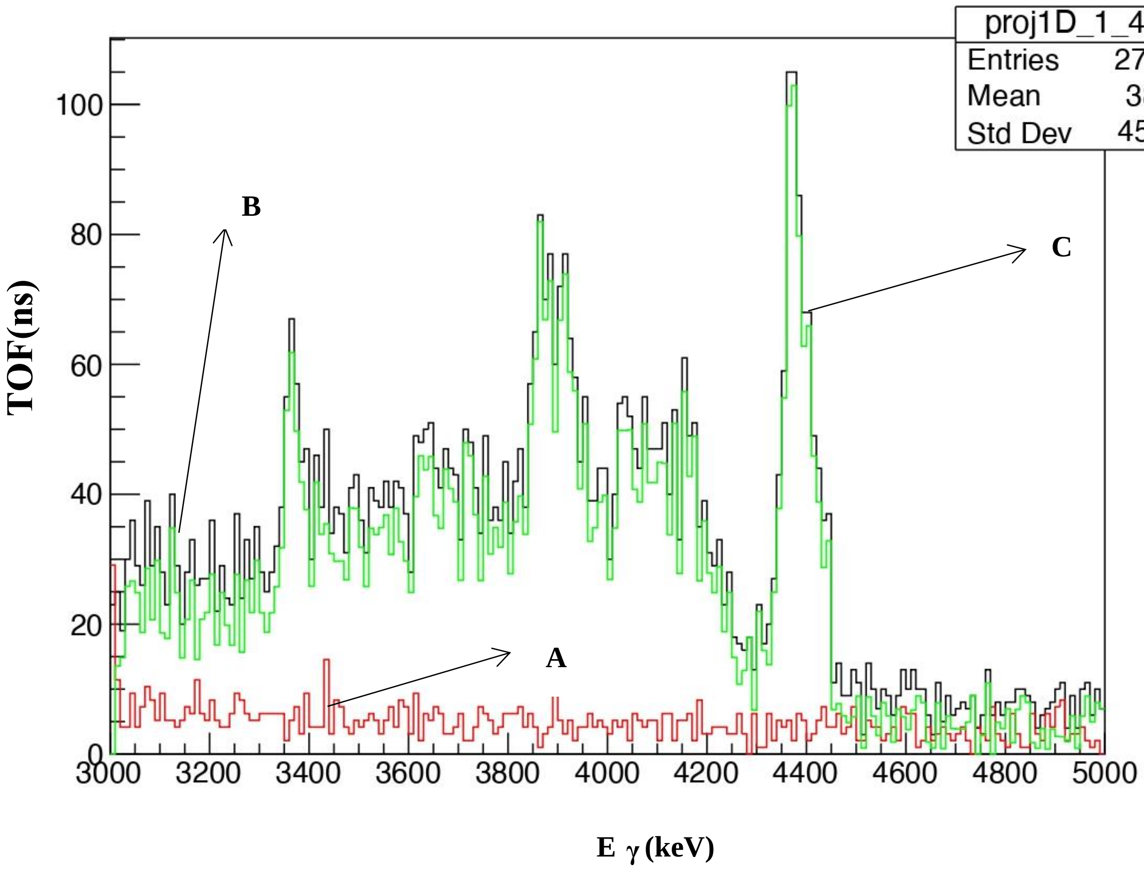

Fig.9 γ-energy spectrum measured with HPGe detectors for ^{12}C. Green line for Subtracted data(**C**) and black one is raw data (**B**)and red one is the Background data(**A**).

In above **Fig.9** shows the energy spectra of gamma ray of gamma ray red line curve is the raw data and the black line show the background data spectra from the environmental interaction and green one is the gamma energy spectra of ^{12}C after (original data) making the subtraction from the raw data to background data for the measurements. From the above **Fig.9** we can say that tagged neutron method is convenient to separate the γ -spectra from the background spectra.
Now we need to determine the photo peak area from the original data for determine the gamma rays yield. To calculate the areas under of γ-peaks, we utilize a Gaussian function and linear or exponential fitting functions. For this experiment we used a Gaussian function with polynomial function of degree 2. At here we have used HPGe detector so we do not need any special kind technique such as analytical function. This is shown in below **Fig.10.**

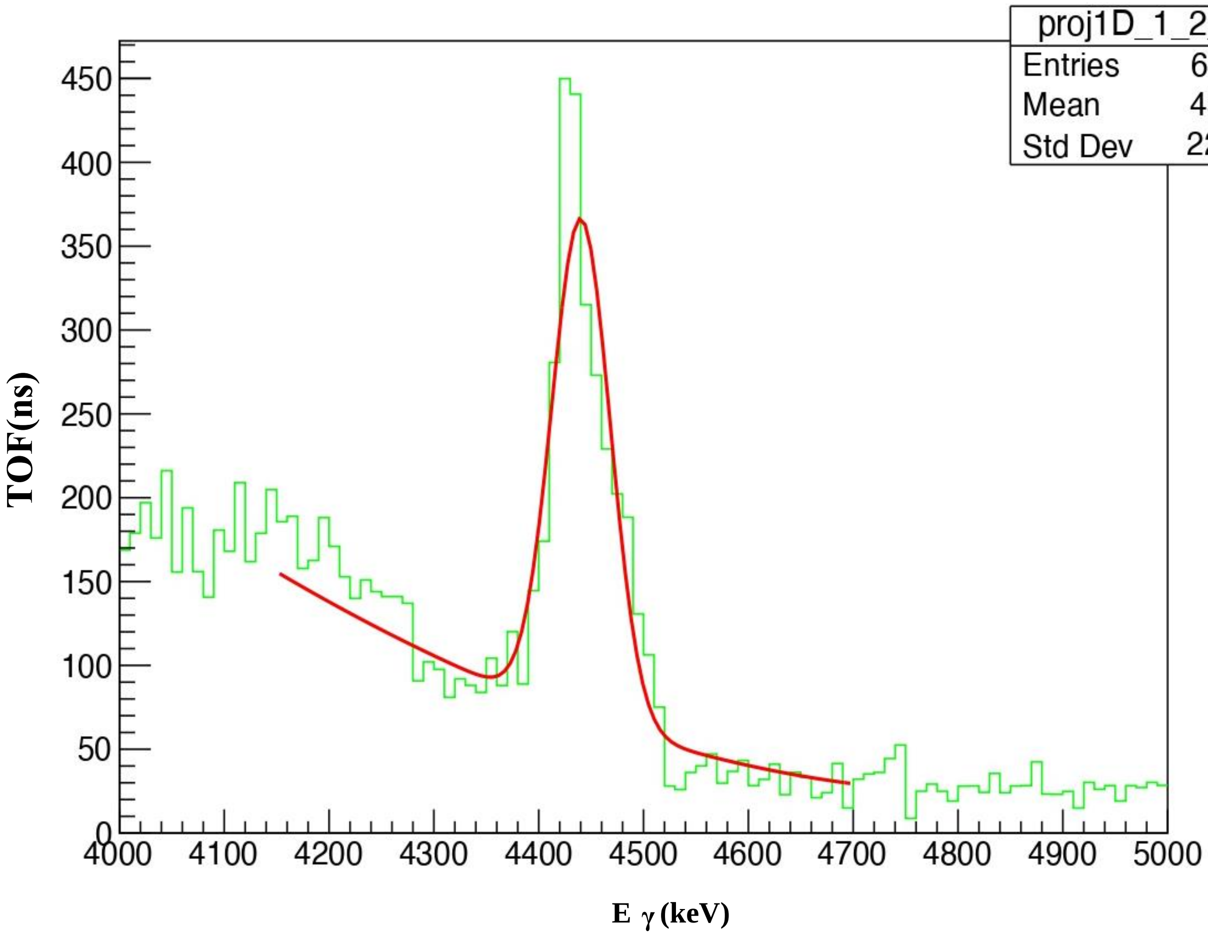

Fig.10 Photo peak fitting of gamma energy spectrum of ^{12}C.

These measurements with HPGe detectors yielded the count of γ- rays of an energy 4339 keV. Detector efficiency and gamma attenuation coefficient are crucial for acquisition. The use of experimental efficiency figures acquired from experiments with calibration isotope sources proves to be inaccurate. γ-quanta detection efficiency and absorption coefficients are unique to each emission point, making it impossible to distinguish them. The coefficient $\varepsilon(E_\gamma)$ is a convolution of detector efficiency and sample absorption, which results in

$$N\gamma = \varepsilon (E\gamma) N\gamma_0$$

Where, N_γ is the number of γ-quanta detected and $N_{\gamma 0}$ is the number of characteristics gamma rays. $\varepsilon(E_\gamma)$ is coefficient was determined as a function of gamma rays' energy from a GEANT4 simulation of experimental setup. Efficiency calculated from the GEANT4 simulation is shown in **Fig.11**

Experiments using the HPGe detector yielded γ-quanta emission yields and cross-sections. To extract these values from experimental data, it's necessary to measure the effectiveness of γ-quanta registration and compensate for γ-ray and neutron absorption within the sample.

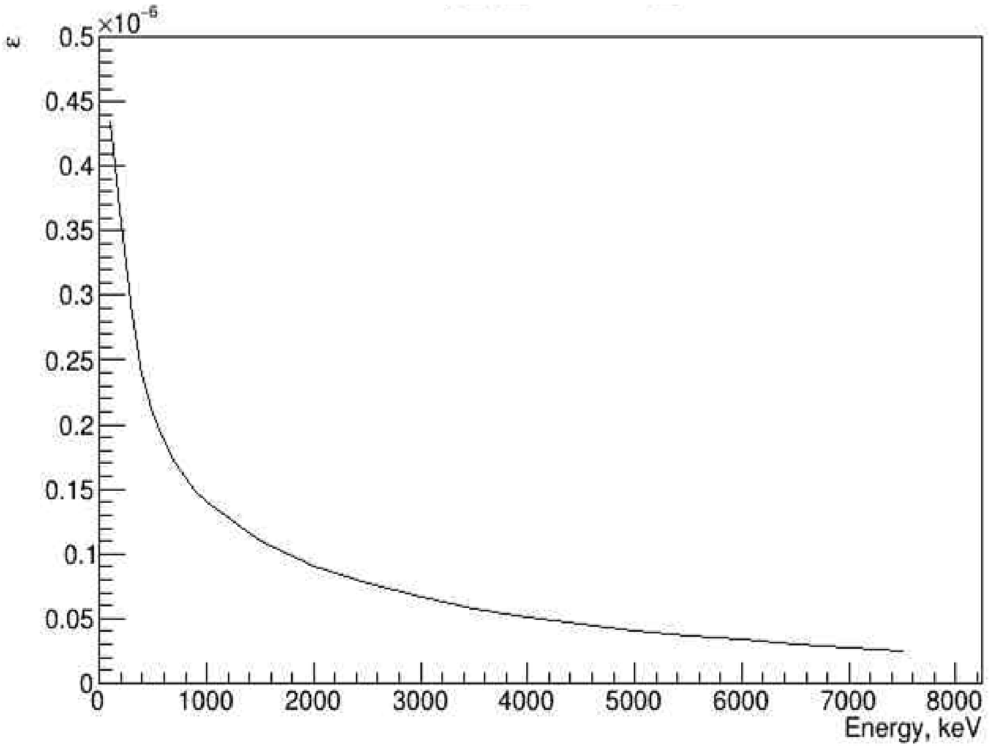

Fig.11 Estimated efficiency from the Monte-Carlo method in GEANT4

4.Results and Discussions

We employed HPGe detectors to assess the good resolution of the gamma-ray spectra. In this experiment, just one gamma transition from the reaction $^{12}C(n, \gamma)$ was monitored with the necessary number of events to register the gamma quanta, as shown in **Fig. 2.**

We have a ^{nat}C sample that contains the isotopes ^{12}C, ^{13}C. However, ^{13}C is a abundant within the 1% range, whereas ^{12}C is almost 99%. So, we were interested in measuring the neutron inelastic cross-section of the ^{12}C. Despite the little amount of contained in the sample, they employed influence to determine the cross-section value for ^{12}C at the 4339 keV gamma quanta energy. To compare, we divided our cross-section value by 4π based on published experimental data in mb/Sr and also used the 1.8 as the correction factor value. **Fig.12** depicts the computed cross-section for this gamma transition energy in comparison to previously published experimental cross-section values. There is a variation between the experimental and published values. We used two experimental data sets and from the nuclear database to validate and compare our determined value.

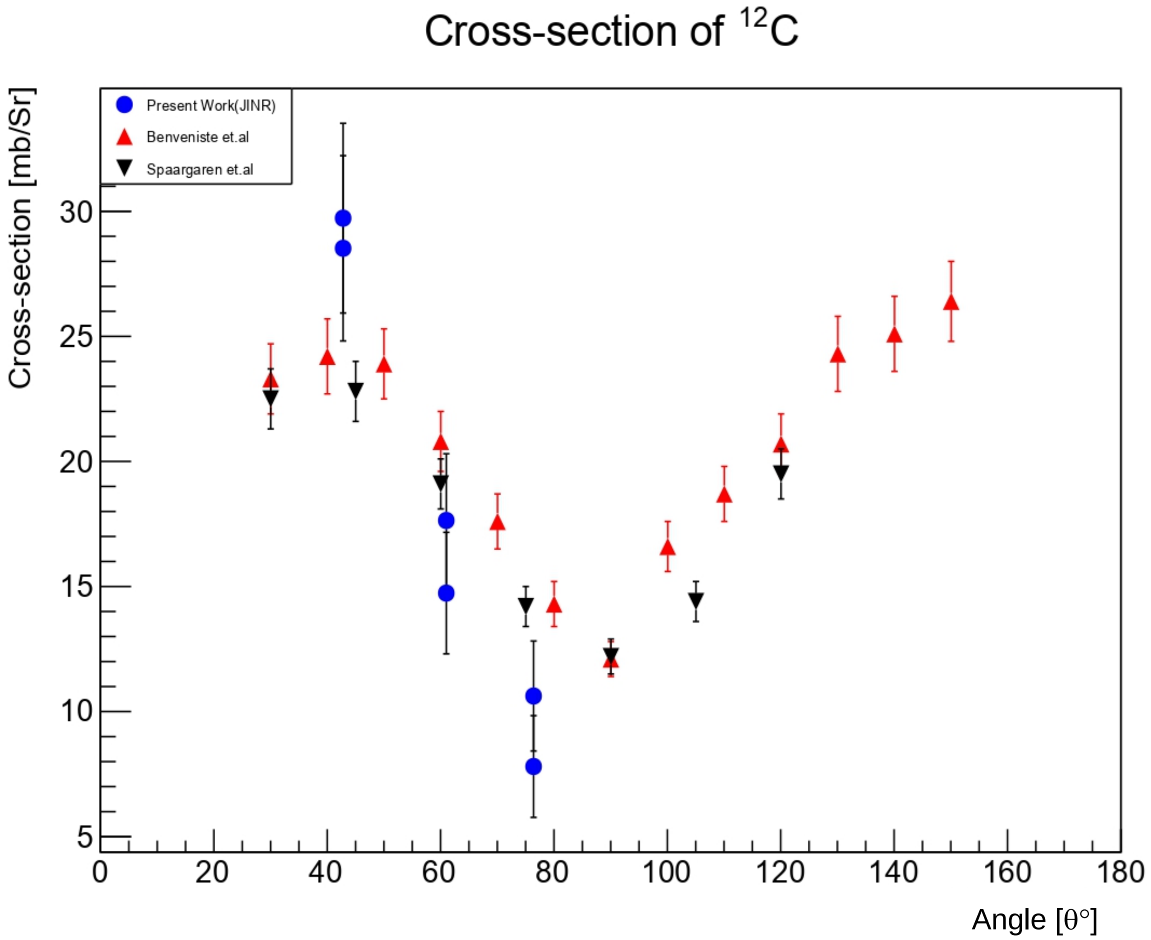

Fig.12 Comparison of the experimentally measured angular distribution for ^{12}C (n, n γ) with the existing experimental data.

The calculated cross-section for the ^{12}C at the gamma energy 4339 keV is given in table with the angle of detector(θ°) and the used formula for this calculation is given below:

$$\left(\frac{d\sigma}{d\Omega}\right)_\theta = \frac{N(\theta)}{N(\alpha)CN(nucl)} \times \cos(\psi) \times 10^{27} \left(\frac{mb}{sr}\right),$$

$$C = \epsilon d\Omega, \quad N_{nucl} = \frac{\rho N(a)D}{A}$$

Where:

θ -is the angle between the beam and the direction towards the detector from the point of interaction of the beam with the target

N(θ)-count of the neutron detector for the angle θ in coincidence with the X strip of the alpha detector

$N(\alpha)$-Neutron counting (alpha detector count without coincidence)

C-correction factor

ϵ-neutron detector intrinsic efficiency

$d\Omega$-solid angle covered by a neutron detector [1/sr]

N_{nucl}-average number of nuclei
A-mass number of target atoms = 12 [g/mol]
ρ-target density = 1.6405 [g/cm3]
N_a-Avogadro's number = 6.02 x 1023 [1/mol]
D-target thickness = 2 [cm]
Cos(ψ)-angle between beam and axis of symmetry

For the uncertainty calculation of measure cross-section value, we have used standard statistical approaches.

5.Conculsion

TANGRA is a remote facility capable of doing research in a variety of subjects. For example, utilizing fast neutrons, we may determine the material composition throughout the entire volume of material. It is also useful in medical research, and this facility offers numerous benefits. The neutron inelastic cross-section for the ^{12}C(n, nγ) reaction was determined for the fast neutron scattering with an energy of 14.1 MeV using the tagged neutron facility at FLNP, JINR. The inelastic cross-section generation of 4339 keV gamma rays by the ^{12}C(n, n γ) reaction is consistent with previous research. However, considerable variances are detected for some cross-section value point. In this study, we studied the angular distribution for the ^{12}C(n, n γ) reaction using only two HPGe detectors. In the future, we intend to investigate this angular distribution utilizing a large number of detectors at various angles from the multi-sectional alpha detector. In addition, we can vary the setup of our multi-sectional alpha detector. For this experiment, we employed a $3 \times 3\, matrix$ strip multi-sectional alpha detector. We need to conduct additional research on this reaction to expand the nuclear data library and achieve good agreement with previous nuclear data on ^{12}C using TNM utilizing a larger detector and $8 \times 8\, matrix,$ Strips (64 pixle) multisectional alpha detectors.

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