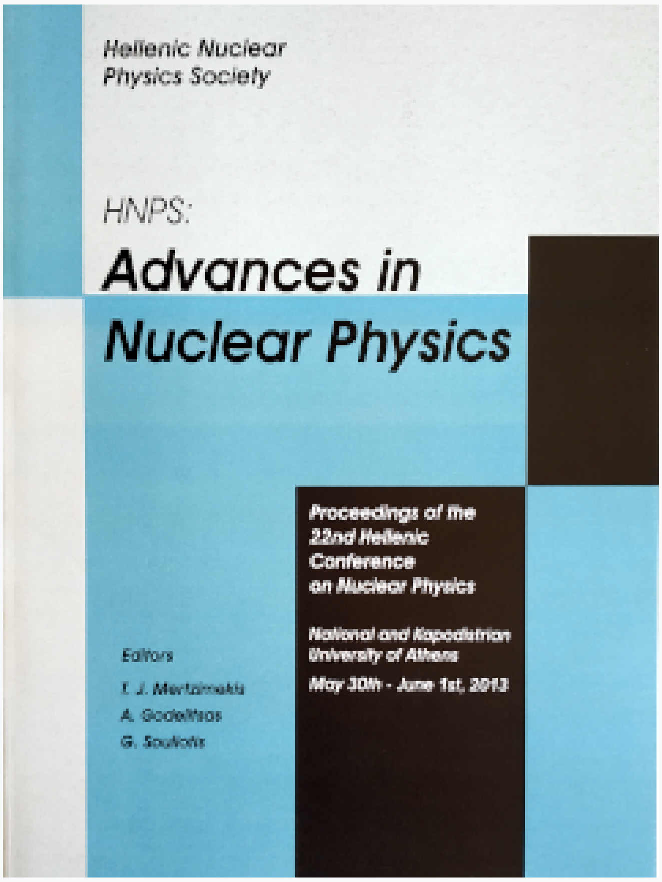
HNPS Advances in Nuclear Physics

Vol 21 (2013)

HNPS2013



High-energy neutron facility at the Athens Tandem Accelerator NCSR "Demokritos"

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doi: [10.12681/hnps.2015](https://doi.org/10.12681/hnps.2015)

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Abstract

In the 5.5 MV tandem T11/25 Accelerator Laboratory of NCSR "Demokritos" monoenergetic neutron beams have been produced in the energy range ∼16–19 MeV using a new Ti-tritiated target of 373 GBq activity, by means of the ^{3}H(d,n)^{4}He reaction. The corresponding beam energies obtained from the accelerator, were 0.8–3.7 deuterons. The maximum flux has been determined to be of the order of 10^6 n/s·cm^2, implementing reference reactions. An investigation of the energy dependence of the neutron fluence has been carried out with the multiple foil activation technique. The beam has been used for the measurement of (n,2n) reaction cross section on several isotopes at 16.7 and 17. MeV.

1. Introduction

Studies of neutron-induced reactions are of considerable significance, both for their importance to fundamental research in Nuclear Physics and Astrophysics and for practical applications in nuclear technology, medicine and industry. These tasks require improved nuclear data and high precision cross sections for neutron-induced reactions. It is thus of importance that the performance of the neutron source is well understood and that the experimental conditions are well characterized [1]. At the 5.5 MV Tandem T11/25 Accelerator Laboratory of NCSR "Demokritos" quasi-monoenergetic neutron beams can be produced with a maximum flux of the order of 10^6 n/s·cm^2, in the energy range ∼4–11.2 MeV by using the ^{2}H(d,n) reaction, at the corresponding deuteron beam energies 0.8–8.2 MeV [2]. These neutron beams have been used for neutron-induced cross section measurements mainly with the activation method [3–9]. This neutron facility has been characterized by means of MCNP5 Monte Carlo simulations, multiple foil activation unfolding technique and deconvolution of recoil energy spectra taken with the BC501A liquid scintillator detector at various neutron energies [10]. However, in order to validate different model calculations and investigate reaction mechanisms, data are needed at higher energies, above 15 MeV, where the pre-equilibrium emission (PE) becomes important.

In view of the above remarks, a new Ti-tritiated target of 373 GBq activity has been installed at the 5.5 MV Tandem T11/25 Accelerator of NCSR "Demokritos", to produce neutrons in the energy range ∼16-19 MeV by means of the ^{3}H(d,n)^{4}He reaction. In absence of time-of-flight capabilities, the energy spectrum of the neutron beam has been investigated by means of the Multiple Foil Activation Analysis technique, using reactions with different energy thresholds. The neutron beam flux has also been investigated by using reference reactions, such as ^{197}Au(n,2n), ^{27}Al(n,α) and ^{93}Nb(n,2n), whose cross sections are well determined in literature.

2. The new high-energy neutron facility

In the 5.5 MV tandem T11/25 Accelerator Laboratory of NCSR "Demokritos" a new neutron facility has been installed, producing beams at energies ∼16–19 MeV by means of the ^{3}H(d,n)^{4}He reaction. The corresponding beam energies obtained from the accelerator, were 0.8–3.7 deuterons. The new Ti-tritiated target of 373 GBq activity, consists of 2.1 mg/cm^2 Ti–T layer on a 1–mm thick Cu backing for good heat conduction. As a trial case of the facility, the deuterons were accelerated to energy 2.0 MeV and passed though two 5–m Mo foils in order to degrade their energy to 0.9 MeV, where the cross section of the ^{3}H(d,n)^{4}He reaction is high enough to produce neutron beam at 16.7 MeV at a flux of the order of $\sim 10^6$ n/s·cm^2. The flange with the tritium target assembly was air cooled during the deuteron irradiation. Two collimators of 2–mm diameter were used and the beam current was measured both at the collimators and the target (see Fig. 1).

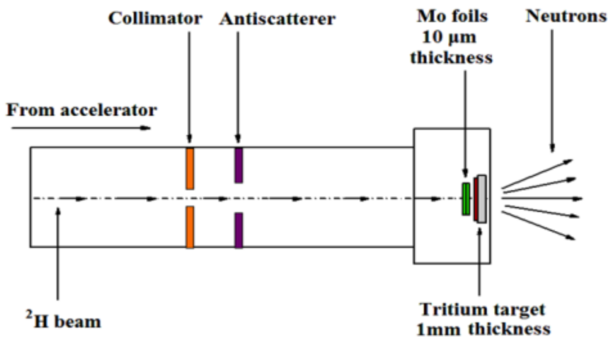

Figure 1: The tritium target assembly in the deuteron beam-line

The flux variation of the neutron beam was monitored by a BF3 detector placed at a distance of 2 m from the neutron production. The spectra of the BF3 monitor were stored at regular time intervals (~100 sec) in a separate ADC during the irradiation process. The absolute flux of the beam was obtained with respect to reference reactions, such as ^{197}Au(n,2n), ^{27}Al(n,α) and ^{93}Nb(n,2n), whose cross sections are well determined in the literature. The reference foils were placed at a distance of 2 cm from the neutron beam production and were irradiated for several hours. The induced activity of product radionuclides from the various irradiated foils was measured with three HPGe detectors of 16%, 50% and 100% relative efficiency, properly shielded with lead blocks to reduce the contribution of the natural radioactivity. The efficiency of the detectors at the position of the activity measurements (10 cm) was determined via a calibrated ^{152}Eu source.

The neutron flux was determined by measuring the characteristic gamma rays from the decay of the residual nuclei, corrected for self absorption of the sample, coincidence summing effects of cascading gamma rays and counting geometry. Furthermore, the decay of product nuclides over the whole time range and the fluctuation of the neutron beam flux over the irradiation time were taken into account. **The deduced flux of the neutron beam at 16.7 MeV, is** $\sim 5 \times 10^6$ **n/s· cm^2**. Another test has been performed with deuteron beam at 2.5 MeV, reduced to 1.5 MeV by the two 5–μm Mo foils, resulting in neutrons **at 17.5 MeV**. At this energy though, the cross section of the ^{3}H(d,n)^{4}He reaction is lower and **the flux of the produced neutrons was** $\sim 8 \times 10^5$ **n/s·cm^2**. The uncertainty of the neutron beam energy has been estimated from the energy loss of the deuteron beam in the Mo foils as well as from the kinematics of the ^{3}H(d,n)^{4}He reaction to be of the order of **200 keV**.

3. Study of the neutron-beam energy distribution

The neutron beam is not purely monoenergetic due to parasitic neutrons mainly coming from deuteron break up reactions: ^{3}H(d,pn)^{3}H, ^{2}H(d,n)^{3}He and reactions with Ti(d,n), O(d,n) and C(d,n). In absence of time-of-flight capabilities, the energy spectrum of the neutron beam has been investigated by means of the Multiple Foil Activation Analysis technique, using reactions with different energy thresholds, as shown in Table 3. The table contains the information concerning the energy threshold E_{thr} of each reaction and the effective energy threshold E_{thr}, where the reaction cross section becomes high enough to yield measurable reaction rates, the half lives $T_{1/2}$ of the residual nuclei along with the most prominent gamma-rays E_γ resulting from their deexcitation and their intensity I_γ.

Reaction	$T_{1/2}$	E_γ [keV]	I_γ	E_{thr} [MeV]	E'_{thr} [MeV]
^{27}Al(n,α)^{24}Na	14.96 h	1369	100%	3.25	6.8
^{58}Ni(n,p)^{58}Co	70.82 d	810.78	99.45%	0	1.4
^{93}Nb(n,2n)^{92m}Nb	10.1 d	934.44	99.07%	8.93	9
^{197}Au(n,2n)^{196}Au	6.18 d	356	87%	8.11	8.2
^{197}Au(n,γ)^{198}Au	2.69 d	411	98.6%		
^{56}Fe(n,p)^{56}Mn	2.58 h	846.75	98.9%	2.97	6.0
^{59}Co(n,α)^{56}Mn	2.58 h	846.75	98.9%	0	9.1
^{115}In(n,n')^{115m}In	4.49 h	336.24	45.8%	0.5	1
^{46}Ti(n,p)$^{46m+g}$Sc	83.83 d	889.3 1120.5	99.98% 99.99%	1.8	3.5
^{47}Ti(n,p)^{47}Sc	3.34 d	159.4	68%	0	2.3
^{48}Ti(n,p)^{48}Sc	1.82 d	983.5	100%	3.2	7.0
^{64}Zn(n,p)^{64}Cu	12.7 h	511	35.7%	1	2.5

Table 1: Reactions used for the multiple foil activation technique and their characteristic properties

High-purity natural foils for all the above mentioned reactions, of 1.3–cm diameter, were placed in close contact at a distance of ∼2 cm from the tritium target for irradiation, as shown in Fig. 2. After a 26 h irradiation, the induced activities of product radionuclides were measured off-line by HPGe detector systems and the neutron beam flux on the foils was deduced, by utilizing cross-section values for each reaction from the data basis ENDF. Preliminary results are presented in Fig. 3.

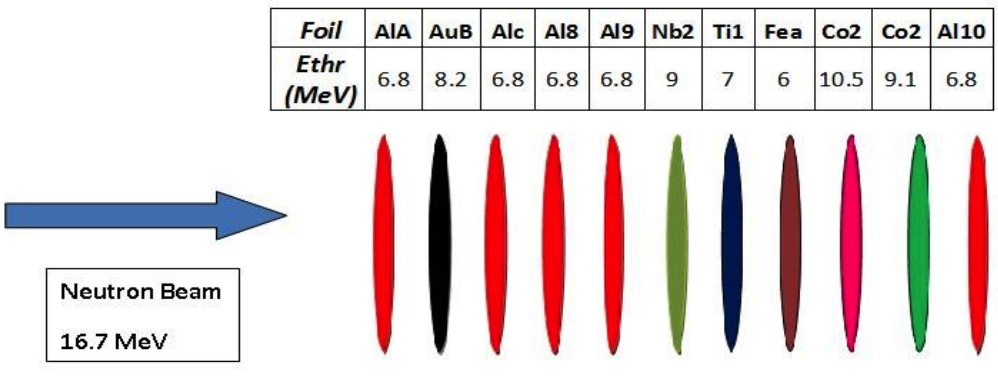

Figure 2: The foil assembly irradiated with the 16.7 MeV neutron beam

The flux gradient of the neutrons in the sample stack, presented in Fig. 3, seems to follow the expected decrease as the neutrons pass through 10 foils, reducing from $\sim 5 \times 10^6$ n/s·cm^2 at the front Al foil (AlA) to $\sim 2 \times 10^6$ n/s·cm^2 at the back Al foil (Al10). It is also interesting to notice the smooth variation of the neutron flux among the 5 irradiated Al foils (AlA, Alc, Al8, Al9 and Al10), indicating that some minor discrepancies between foils of different materials (as for example Fe and Co), are probably due to the cross section values used to deduce the flux.

At 2 MeV deuteron energy, the neutron energy spectrum is expected to contain parasitic neutrons in the region 1–5 MeV, associated with the ^{2}H(d,n)^{3}He and ^{12}C(d,n) reactions [1]. A comprehensive understanding

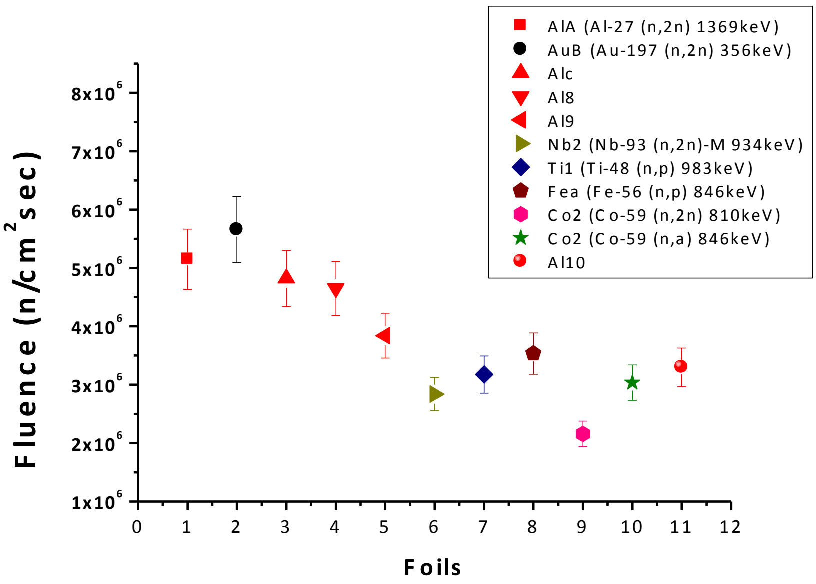

Figure 3: Fluence of neutron beam at 16.7 MeV on successive irradiated foils

of the energy dependence of the neutron flux is of major importance for the reliability of neutron-induced reaction cross-section measurements. Thus, in order to determine the neutron flux energy distribution of our facility, the unfolding method is planned to be applied to these multiple foil activation results in the near future. In the mean time, only threshold reactions can be safely measured with monoenergetic neutrons, since the low energy parasitic neutrons involved in the beam, cannot affect the cross-section measurements.

Four such threshold reactions have been investigated. The ^{241}Am(n,2n)^{240}Am reaction has been measured at 17.5 MeV and the results are presented in another contribution in these Proceedings. In addition, the reactions that have been studied by our group at lower energies [6–8], were measured at 16.7 and 17.5 MeV, in order to extend the investigation at higher energies. The analysis of these data is currently in progress.

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