Characterization of the RFT-30 Neutron Source Using Multi-Sample Neutron Activation Analysis

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1. Introduction

The utility of Accelerator-based neutron sources is determined not only by the total intensity but also by the energy spectrum at the irradiation position. Since neutron interactions with matter are strongly energy dependent making an accurate characterization of the neutron energy spectrum essential for quantitative use of such facilities in applications including radioisotope production, neutron-induced cross-section measurements, and radiation-effects studies [1-4]. At the Advanced Radiation Technology Institute (ARTI), the RFT-30 cyclotron provides a 30 MeV proton beam with an average current of 10 μA for neutron production via irradiation of a thick beryllium target [5]. Despite the broad utilization of this source the energy spectrum of the neutrons produced on the beam line has not yet been fully characterized, motivating the development of an efficient and reliable approach to determine the neutron flux and its energy distribution over a broad range of neutron energies. Neutron activation analysis (NAA) provides a practical route to this problem. NAA is a highly sensitive, non-destructive method identifies and quantifies elements by irradiating a sample with neutrons and analyzing the characteristic gamma rays emitted from activation products [6]. By selecting foils that include both thermal neutron capture reactions and fast-neutron threshold reactions, neutron spectrum can then be reconstructed using an unfolding procedure [7]. In this work, we apply the multi-foil activation method to determine the neutron spectrum of the 30 MeV Proton Cyclotron-Based Neutron Source at ARTI. The unfolded spectrum is discussed and compared with Monte Carlo results obtained using the MCNP6.3.

2. Methods and Results

2.1 Neutron activation experiment

Neutrons are generated by irradiating a thick beryllium target with a 30 MeV proton beam extracted from the RFT-30 cyclotron. Four activation samples (Al, Co, Fe, and Nb) were prepared as cylinders with a diameter of 10 mm and a thickness of 5 mm. Fig. 1 shows the schematic of the activation experiment, including the sample position on the neutron beam line. Samples were irradiated simultaneously on the neutron beam line for 2 hours at an average beam current of 10 μA. After irradiation, the samples were retrieved and transferred to the calibrated High-Purity Germanium (HPGe) detector for gamma-ray spectroscopy.

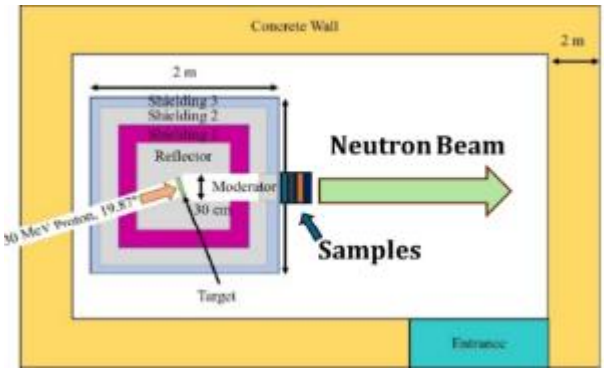

Fig. 1. Schematic layout of the sample position on the neutron beam line

2.2 Gamma ray spectroscopy measurements

$$N = \frac{C_{net}}{t_M I_\gamma \varepsilon_\gamma} \cdot \frac{\lambda t_M}{(1 - e^{-\lambda t_A}) \cdot e^{-\lambda t_D}(1 - e^{-\lambda t_M})} \#(1)$$

Activities are calculated from the measured full-energy peak counts with corrections for detector efficiency, gamma-ray emission probability, and decay during irradiation, cooling, and counting, as summarized in Eq. (1). C_{net} is the net peak count, t_M is the live counting time, ε_γ is the full-energy peak efficiency of the HPGe detector at the selected gamma-ray energy, I_γ is the emission probability of the selected gamma ray, and λ is the decay constant of the activation product. t_A is the irradiation time, t_D is the cooling time. Energy and efficiency calibrations were performed using standard gamma sources over the energy range relevant to the activation products. Full-energy peak areas were obtained by peak fitting after background subtraction. Counting dead time was monitored and maintained at a level where dead-time corrections were reliable.

2.3 Neutron unfolding

The neutron spectrum can be obtained through the spectrum unfolding when measured activities and the response function are related. The activity for each foil can be derived, as Eq. (2).

$$N_i = \sum_j R_{ij}\,\phi_j \#(2)$$

Here N_i represent the measured activity of ith reaction, $R_{i,j}$ is the response function related to activity with the i-th reaction for the j-th energy group. To reconstruct the neutron spectrum ϕ_j from the measured activities, Eq. (2) must be inverted. We employed the GRAVEL algorithm, an iterative spectrum unfolding method, as shown in Eq. (3).

$$\phi_j^{n+1} = \phi_j^n \exp\left(\frac{\sum_i W_{ij}^n \log\left(\frac{N_i}{\sum_j R_{ij}\,\phi_j^n} \right)}{\sum_i W_{ij}^n} \right) \#(3)$$

In Eq. (3) ϕ_j^n is the neutron flux after the nth iteration, W_{ij}^n is a weight factor defined as Eq. (4).

$$W_{ij}^n = \left(\frac{R_{ij}\phi_j^n}{C^n} \right) \cdot \frac{N_i^2}{\sigma_i} \#(4)$$

In this work σ_i denotes the standard deviation of the measured activity, where $\sigma_i = \sqrt{N_i}$

$$\delta^n = \frac{\left\| \phi_j^n - \phi_j^{n-1} \right\|}{\max\left(\left\| \phi_j^{n-1} \right\| \right)} \#(5)$$

Since iterative unfolding algorithms require a stopping criterion, the unfolding was considered converged when the relative change metric, δ^n became sufficiently small[8]. Initial spectrum ϕ_j^0 was obtained using MCNP6.3 and was used as the prior spectrum for the GRAVEL unfolding.

2.4 Response function

The response function represents the energy-dependent sensitivity of each activation reaction to the incident neutron spectrum. The response functions were generated using FISPACT-II with the TENDL-2017 nuclear data library. Fig. 2 shows the normalized response functions for the selected reactions. The 59Co(n,γ)60Co exhibits strong sensitivity in the thermal neutron region, whereas the threshold reactions such as 27Al(n,p)27Mg, 27Al(n,α)24Na, 56Fe(n,p)56Mn, 93Nb(n, α)90mY, 93Nb(n,2n)92mNb, 59Co(n,α)56Mn and 59Co(n,2n)58Co provide sensitivity to the fast-neutron region.

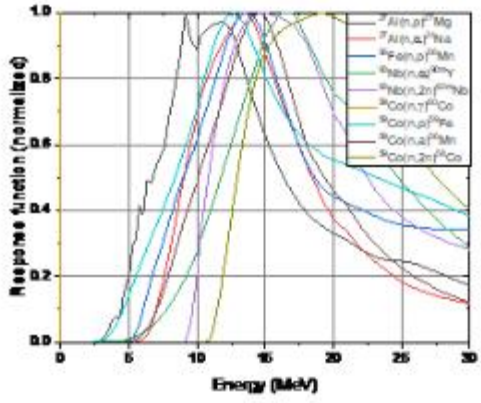

Fig. 2. Normalized response function of each reaction obtained by 2017-TENDL 709 neutron energy group using FISPACT-II

2.5 Unfolding results

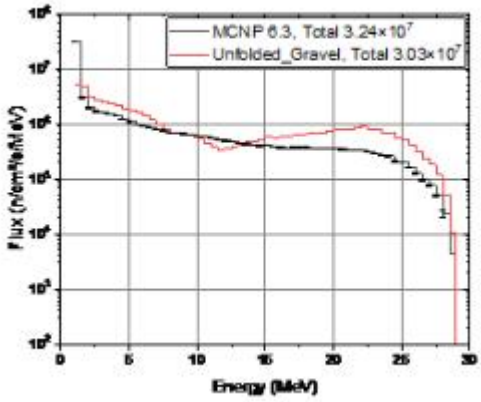

Fig. 3 Comparison between MCNP6.3 simulations and unfolding results

Flux obtained from the unfolding agrees with the MCNP6.3 result within 7% (Fig. 3), The unfolded spectrum yields a lower thermal neutron flux and a higher fast-neutron flux than the simulation. The thermal region is strongly constrained by capture-dominated reactions, while the fast-neutron region is adjusted by multiple threshold-reaction constraints. Neutron energy Flux over the 15 MeV exhibits more pronounced shape modifications after unfolding, due to the absent of the threshold reaction in this region.

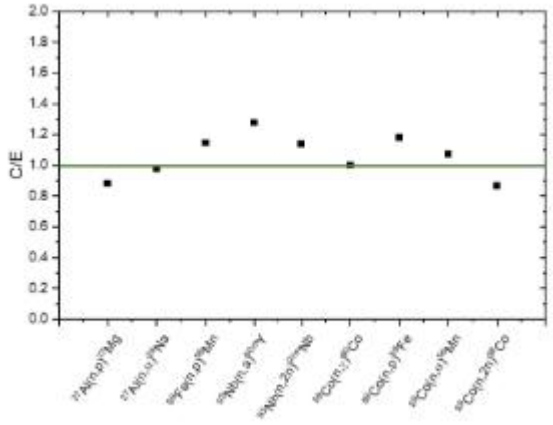

Fig. 4 Comparison of the measured activities and activities calculated from unfolded spectrum

The unfolded neutron flux spectrum was used to recalculate the activity for each monitored reaction by folding the flux with the corresponding response function, as in Eq. (2.2). The calculated-to-experimental ratio (C/E) was evaluated for each reaction, and Fig. 4 summarizes the results. The unfolded spectrum reproduces the measured activation observables within ±27%. Notably, the thermal capture reaction shows a C/E close to unity, as expected, because capture reactions provide a strong integral constraint on the thermal neutron region.

3. Conclusions

In this study, the neutron energy spectrum of the RFT-30 accelerator-based neutron source was characterized over 0–30 MeV using a multi-foil activation with GRAVEL unfolding algorithm. Al, Co, Fe, and Nb foils were selected to provide sensitivity via capture and threshold reactions. The total neutron flux obtained from the unfolding agrees with the MCNP6.3 result within 7%. The unfolded spectrum was further validated by reconstructing the activities of the monitored reactions the thermal capture reaction exhibits a C/E close to unity. The resulting reference spectrum can support irradiation planning, radioisotope production, cross-section validation and Investigation of the radiation hardness on semiconductors. The accuracy of the reconstructed spectrum can be further improved by expanding the activation set to include additional foils with diverse threshold energies, particularly reactions with higher thresholds approaching the upper end of the neutron spectrum.

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