Neutron Filtering System for Fast Neutron Cross-section Measurement at ANNRI

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Abstract

The double-bunch pattern of the J-PARC facility introduces serious ambiguities in the neutron-induced cross-section measurement for fast neutrons. The neutron filtering technique is implemented in the ANNRI beamline in order to produce quasi-monoenergetic neutron peaks. Different filter configurations with Fe and Si were tested by means of capture and transmission experiments and with Monte-Carlo simulations using the PHITS code. In this work, the characteristics of the neutron filtering system using Fe and Si are presented together with a preliminary cross-section results for the ^{197}Au neutron capture cross-section.

1 Introduction

The double-bunch mode is employed in the Japanese Proton Accelerator Research Complex (J-PARC) in which two 0.1 μs-wide proton bunches are shot into a spallation target with a time difference of 0.6 μs at a repetition rate of 25Hz. This mode is intended to increase the thermal neutron beam intensity as, for that energy, the doublet structure of the neutron beam is negligible due to Doppler broadening and moderation time. Nonetheless, for fast neutrons experiments in the Accurate Neutron-Nucleus Reaction Measurement Instrument (ANNRI) beamline, this time difference is no longer trivial. Fast neutrons reach the target position within 10 μs and the 0.6 μs time difference becomes a significant source of ambiguities in the cross-section measurements. Neutrons detected with a certain time-of-flight (TOF) can have two different energies as it is impossible to ascertain the originating proton bunch. For example, for the case of 100 keV neutrons, the expected TOF for the NaI(Tl) spectrometer target position is about 6.4 μs. However, at 6.4 μs, neutrons with an energy of 120 keV coming from the delayed proton shot can also be detected. In this work, we propose a solution to bypass the double bunch structure of ANNRI using a neutron filtering system. The characteristics and performance of the neutron filtering system implemented at ANNRI are presented in this paper. The filtering system was analyzed using both experimental analysis and Monte-Carlo simulations.

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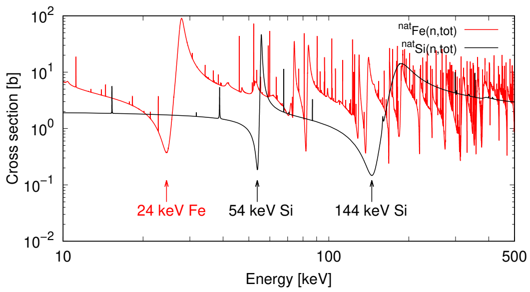
2 Neutron Filtering System

A neutron filtering system has been designed at the ANNRI beamline in order to circumvent the double-timed structure of the neutron beam within the "Study on accuracy improvement of fast-neutron capture reaction data of long-lived MAs for development of nuclear transmutation systems" project [1]. Using the neutron filtering tecnique, the incident white neutron flux can be tailored into quasi-monoenergetic peaks using materials that present a sharp minimum in the neutron total cross-section [2]. Several cylinders of ^{nat}Fe and ^{nat}Si were used in different configurations and expected to create quasi-monoenergetic filtered neutron peaks with energies of 24 keV (Fe) and 54 and 144 keV (Si).

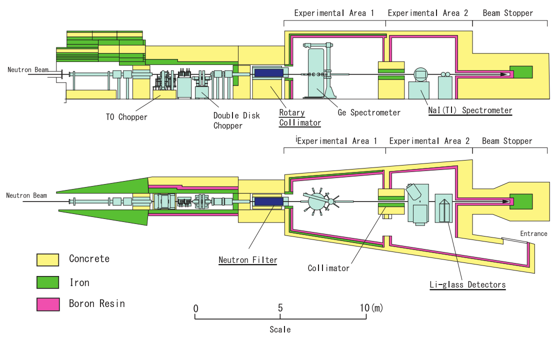
3 Experimental Analysis

3.1 Neutron Filtering Setup

The neutron total cross-section for ^{nat}Fe and ^{nat}Si can be seen in figure 1(a). Neutron filtered peaks are expected with energies of 24, 54 and 144 keV. Three different filter assemblies consisting of 20 cm of Fe and 20 and 30 cm of Si were implemented in the rotary collimator of the ANNRI beamline (see Fig. 1(b)).



(a)



(b)

Figure 1: (a)Neutron total cross-section of ^{nat}Fe and ^{nat}Si. (b) Schematic view of the ANNRI beamline. The neutron filter material was introduced in the rotary collimator.

3.2 Neutron Capture Experiments

The NaI(Tl) spectrometer of the ANNRI beamline was employed to determine the filtered incident neutron flux [3]. The samples were situated at a neutron flight path of 27.9 m. A boron sample with a 10 mm diameter and thickess of 0.5 mm and a Au sample with a 10 mm diameter and 1 mm thickness were used in the experiments. The incident neutron flux was determined by measuring the 478 kev γ-rays from the ^{10}B(n,$\alpha\gamma$)^{7}Li reaction. The Au sample measurement was used to normalize the incident neutron flux derived from the boron sample measurement at the energy point of the first resonance (4.9 eV) since it was completely saturated. More information about the experimental analysis can be found here [4].

3.3 Transmission Experiments

The incident neutron flux was also measured in transmission experiment using two types of Li-glass detectors. A Li-glass detectors enriched with ^{6}Li (GS20) and a Li-glass detector enriched with ^{7}Li (GS30) were simultaniously employed in the experiments. The detectors were situated at a flight-path of 28.6 m having the ^{7}Li enriched detector in the upstream position. The GS20 detector is used to detect the incident neutrons via the ^{6}Li(n,α)^{4}He reaction whereas GS30 detector is employed to estimate the background due to γ-rays. Further details on the transmission analysis are provided there [5].

3.4 Experimental Results

The results obtained from both experimental techniques provide very good agreement and are able to show the filtering performance of the neutron filtering system. The results for the Fe filter array of 20 cm is provided is Fig. 2.

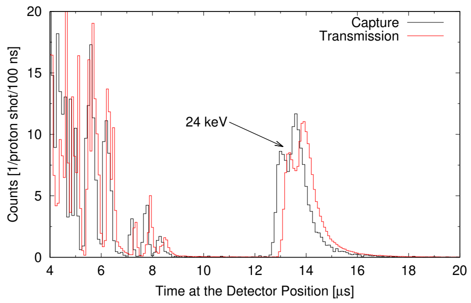
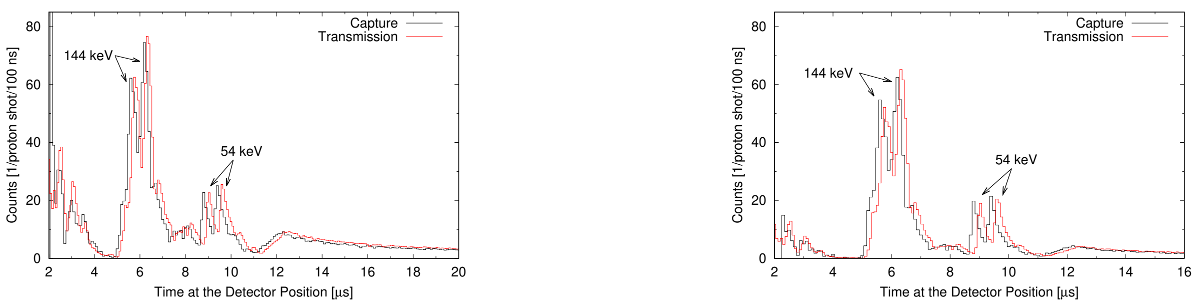


Figure 2: Filtered neutron flux by 20 cm of Fe obtained from capture (black) and transmission (red) experiments.

The filtered neutron peak of 24 keV is clearly isolated for both capture and transmission experiments in one double-humped peak that includes overlapped neutrons from both proton bunches. Other filtered peaks can also be seen between 7 and 9 μs but the counting rate seems to be too small to be used in experiments. The results for the two different Si filter assemblies can be seen in Fig. 3(a) for 20 cm of Si and in Fig. 3(b) for 30 cm of Si. As is the case for the Fe array, both capture and transmission experiments present high agreement for both filtered peaks of 144 and 54 keV. Here the contributions from each proton bunch are clearer as these peaks occur at a higher energy. The difference in time between the results from both detectors is due to the fact that that the detectors are installed at different positions with respect to the incident neutron beam (see Fig. 1(b)). The NaI(Tl) spectrometer is situated at a distace of 27.9 m from the moderator surface whereas the Li-glass detectors are situated at a slightly longer distance of 28.6 m.



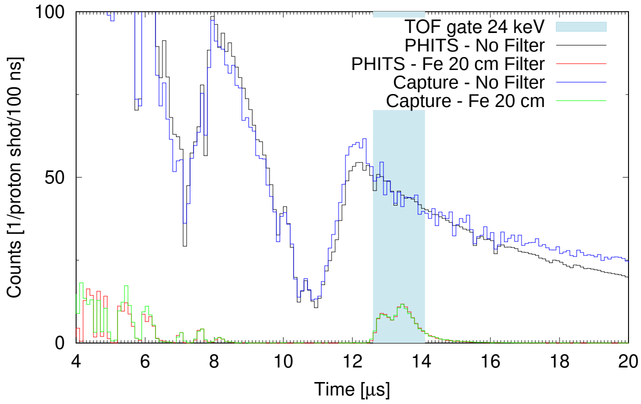
(a) (b)

Figure 3: Filtered neutron flux by 20 cm of Si (a) and 30 cm of Si (b) determined from capture (black) and transmission (red) experiments

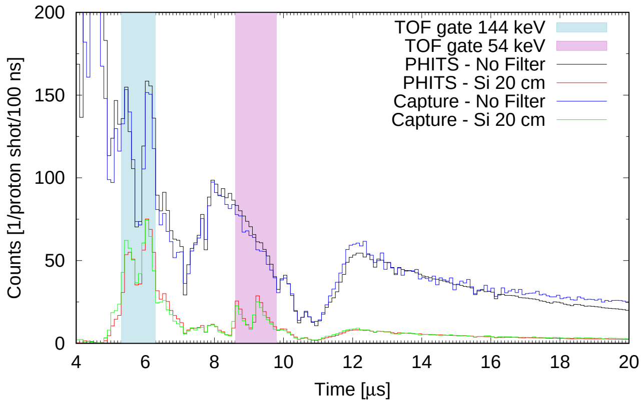
4 PHITS Simulations

Monte-Carlo simulations with the code PHITS [6] were employed as benchmark for the filtering system performance analysis. Since the straight relationship between time and energy for the detected neutrons is no longer applicable for fast neutrons due to the double-bunch structure, simulations with PHITS are used the neutron transmition ratio through all the materials, including not only the filter materials but also structural materials, in the ANNRI beamline. The neutron transmitted ratios were then unfolded taking into account the time structure of the ANNRI beamline as was described by Kino *et al* [7] using the model function suggested by Ikeda and Carpenter [8].

The derived time distribution results from the PHITS simulations can be seen in Fig. 4(a) and 4(b) for the 20 cm Fe and 20 cm Si filter arrays, respectively, compared with the results with no filter present. The PHITS results are also compared with the experimental results obtained from the capture experiments. The Monte-Carlo simulations are able to accurately reproduce the experimental results with both filter assemblies and when no filter material is used. Hence, the energy distribution obtained from the PHITS simulations is deemed reliable.



(a)



(b)

Figure 4: Time distribution of the PHITS results and Capture experiments using a 20 cm Fe filter (a) and a 20 cm Si filter (b) compared with the results when no filter is present.

In order to analyze the neutron energy distribution derived with PHITS at the filtered peaks, TOF gated were created enclosing the three filtered neutron peaks. For the Fe filter array, a TOF gate was created from 12.6 to 14.6 μs to wrap the 24 keV filtered neutron beam. This gate is shown in Fig. 4(a). From the gated TOF data, a centroid energy of 23.6 keV was determined for the Fe 24 keV window. On the other hand, the neutron energy distributuon of the filered peaks of 144 keV and 54 keV were derived using TOF gates from 5.4 to 6.4 μs and from 8.6 to 9.8 μs, respectively. For the Si array, centroid peaks of 127.7 and 51.5 keV were derived from the PHITS results. The result of 127.7 keV is much lower than the expected value of about 144 keV. The reason for this is that the peak is shifted to a lower energy due to the presence of ^{27}Al in the beamline which has a resonance peak at the energy around 150 keV in the neutron total cross-section. Neutrons with energies from 135 to 160 keV are scattered by the several layers of ^{27}Al present at ANNRI used to compartimentalize the beamline and cannot reach the experimental areas.

5 Cross-section results

Preliminary results of the ^{197}Au neutron capture cross-section were derived as the final step to evaluate the perfomance of the neutron filter and their viability for neutron-induced reaction measurement. The Au cross-section was derived from the obtained Au capture yield using the Pulse-Height Weighting Technique (PHWT) [9] at each TOF gate (G_i) using the following:

$$\sigma_{Au}(G_i) = \frac{Y_{Au}(G_i)C(G_i)}{\phi_n(G_i)}\frac{1}{n_{Au}} \tag{1}$$

being $\sigma_{Au}(G_i)$ the absolute cross-section for each of the three TOF gates (G_i); $Y_{Au}(G_i)$ and $C(G_i)$ are the Au neutron capture yield and the coeficient to correct for the self-shielding and multiple-scattering effects for each TOF gate (G_i), respectively. $\phi_n(G_i)$ means the normalized incident neutron flux at the TOF gate (G_i) and n_{Au} stands for the sample area density in at/barn.

The preliminary results for the ^{197}Au neutron capture cross-section are shown in Fig. 5. The results are compared with the JENDL-4.0 evaluated data [10] and the IAEA standard library[11]. The x-axis bar are the mininum and maximun neutron energy determined at each TOF gate by PHITS.

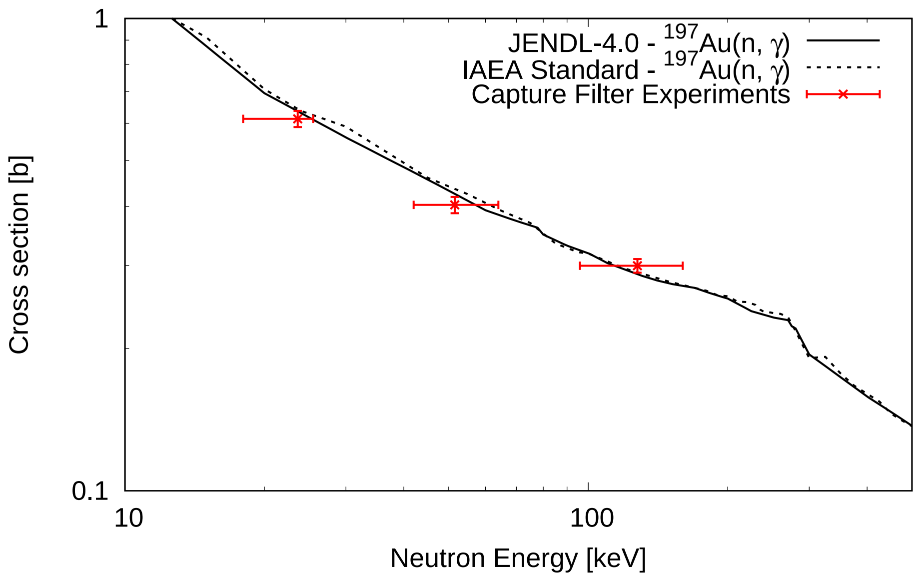


Figure 5: Preliminary results for the ^{197}Au neutron capture cross section using the ANNRI filtering system

The present preliminary results agree within uncertainties with the evaluated data from JENDL-4.0 and present slightly lower values than those included in the IAEA standard library.

6 Conclusions

The neutron filtering system applied in the ANNRI beamline is able to tailor the incident neutron flux into quasi-monoenergetic neutron peaks. The filter configurations of 20 cm of Fe and 20 cm of Si have proven to be a feasible solution in order to circumvent the double-bunch structure for fast neutron cross-section measurements. Using experiments and simulations with PHITS, the characteristics of the three peaks molded by the Fe and Si assemblies were determined with centroid energies of 23.6 keV (Fe) and 51.5 and 127.7 keV (Si). Furthermore, a preliminary cross-section measurement of the ^{197}Au neutron capture cross-section using the neutron filtering system was performed. The present results agree within uncertainties with the evaluated data from JENDL-4.0.

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