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Progress of Filtered Neutron Beams Development and Applications at the Horizontal Channels No.2 and No.4 of Dalat Nuclear Research Reactor

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Abstract: The neutron filter technique has been applied to create mono-energetic neutron beams with high intensity, at the horizontal channels No.2 and No.4 of the Dalat nuclear research reactor. The mono-energetic neutron beams that have been developed for researches and applications are thermal (0.025eV), 24keV, 54keV, 59keV, 133keV and 148keV. The relative intensities of main peak in filtered neutron energy spectra and the collimated neutron fluxes at the sample irradiation positions are 90 ÷ 96% and 2.8×10^5 ÷ 7.8×10^6 n/cm^2.s, respectively. Monte Carlo simulations and transmission calculations were performed to each neutron energy beam for optimal design of geometrical structure and neutron filter materials. These filtered neutron beams have been applied efficiently for experimental researches on neutron total and capture cross sections measurements, and elemental analysis in various kinds of samples based on the prompt gamma neutron activation analysis method. This paper reviews the progress of filtered neutron beams development and its applications for past many years at the Dalat nuclear research reactor.

Keywords: *Filtered neutron beam, nuclear data measurement, Dalat nuclear research reactor*

I. INTRODUCTION

The Dalat nuclear research reactor (DNRR), located in campus of the Nuclear Research Institute, VINATOM, was originally a TRIGA MARK II reactor with a nominal power of 250kW completed construction and reached critical state in 1963. The reactor then has been upgraded to nominal power of 500 kW since 1984. There are three radial and one tangential beam ports at DNRR, each of which penetrates the concrete shield structure and the reactor water to provide external beams of neutron originated from reactor core [1]. The cross section view of horizontal channels of DNRR is shown in Fig.1. The radial beam port No.4 has been used to develop mono-energetic neutron beams of thermal, 54keV and 148keV (previous reported as 55 and 144keV) by the neutron filter technique for basic research on neutron induces nuclear reaction data measurements since 1991 [2]. For efficient and extensive uses of the neutron channel, the neutron filter technique has been also applied to create high intensity neutron beams with quasi-monoenergies of 24keV, 59keV and 133keV at the channel No.4 in 2008 [3].

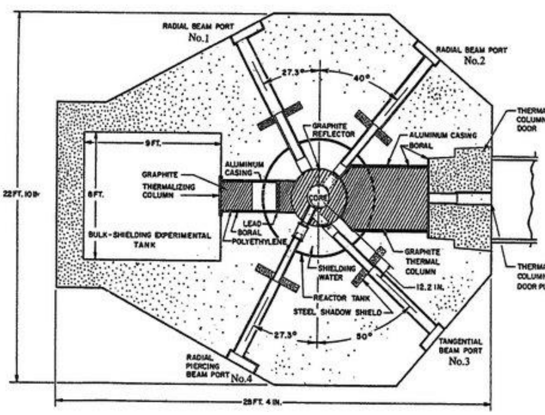

Fig. 1. Structure of horizontal neutron channels of the Dalat nuclear research reactor

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In order to enhance the utilizations of DNRR for neutron capture experiments and prompt gamma-rays neutron activation analysis (PGNAA) applications, the beam port No.2 of the reactor have been opened in advance since 2010 [4] for development of a modern prompt gamma-ray Compton suppression facility used a high efficient HPGe-BGO detectors system. In the works of neutron filters development, the Monte-Carlo simulation used MCNP5 code, and transmission calculation by CFNB code [5] have been performed for each neutron beam for optimal design of geometrical structure, neutron filter materials and radiation shielding.

The applications of these filtered neutron beams were mainly focus on nuclear data measurements and PGNAA elemental analysis, although these beam lines have possibility for many other researches and applications such as nuclear level density and isomer ratio determination, Boron neutron capture therapy (BNCT) research, neutron dosimeter calibrations,... On the nuclear data measurements respects, the channels provide essential neutron beams for precise experimental reaction data of neutron total and capture reaction cross sections. On the PGNAA application subject, the assessment of analytical sensitivity for elements of B, H, Hg, Si, Ca, C, S, Al, Fe, Cl, Ti,... has been carried out, and shown that the new PGNAA spectroscopy installed at the channel No.2 is a good facility supplemented to the neutron activation analysis (NAA) method at the Dalat nuclear research reactor. The detail characteristics of filtered neutron beams development and results of its applications are presented in the next sections.

II. FILTERED NEUTRON BEAMS

The optimal design structure for insertion of filters into the horizontal channel, beam collimators and radiation shielding chamber at the Dalat nuclear research reactor is shown in Fig.2 [4]. The neutron energy spectra after filtered through a suitable composition materials used as filters can be calculated as the following expression:

$$\varphi(E) = \varphi_0(E) * \exp(-\sum_k \rho_k d_k \sigma_{t,k}(E)), \quad (1)$$

where $\phi_0(E)$, $\phi(E)$ are energy distributions of the neutron spectra before and after transmitted through the filters; ρ_k, d_k and $\sigma_{t,k}(E)$ are the mass density, length of filter and total cross section of k^{th} filter material, respectively. The filter information and physical parameter of each energy beam is presented in the following sub-sections.

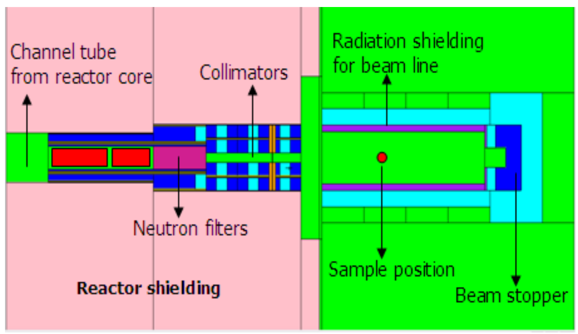

Fig. 2. The design structure of filtered neutron beam facility at the channel No. 2 of DNRR

The thermal neutron beams:

The thermal neutron beam at the channel No.4 was developed in 1991 [2]. The material compositions of filters are 98cm Si, 1cm Ti and 35g/cm^2 S. The measured thermal neutron flux is 1.7×10^6 n/cm^2.s, and Cadmium ratio R_{cd}(Au) = 112 [3]. In order to enhance the utilizations of the Dalat research reactor for researches and applications based on the neutron capture reactions, the well thermal neutron beam at the channel No. 2 has been developed and serviced since 2011 [4]. The neutron filters for this 0.0253eV neutron beam line are single crystals of 80cm Si and 6cm Bi. The measured thermal neutron flux at outer position of the beam line is 1.6×10^{6} n/cm^2.s, and the value of Cadmium ratio R_{cd}(Au) is 420.

The neutron beams of 54keV and 148keV:

The neutron filter technique has been applied at the horizontal channels of Dalat nuclear research reactor from 1990s [2, 3]. Firstly, the two neutron beams with mono-energies of 54keV and 184keV were created at the channel No.4, and provided a good experimental station for basis researches on reactions of neutron with material in keV energy region. The filter information and physical parameters of these neutron beam lines are introduced in Table I [3], and the corresponding neutron spectra are shown in Figs. 3-4.

Table I. Physical parameters of the 54keV and 148keV neutron beams at the channel No.4

Parameters	**54keV**	**148keV**
Neutron flux (n/cm^2.s)	6.7x10^5	3.9x10^6
Energy resolution (keV)	1.5	14.8
Peak relative intensity (%)	78.05	95.78
Beam collimated diameter	3 cm	3 cm
Filter compositions	B 0.2g/cm^2 Si 98cm S 35g/cm^2	B 0.2g/cm^2 Si 98cm Ti 1cm

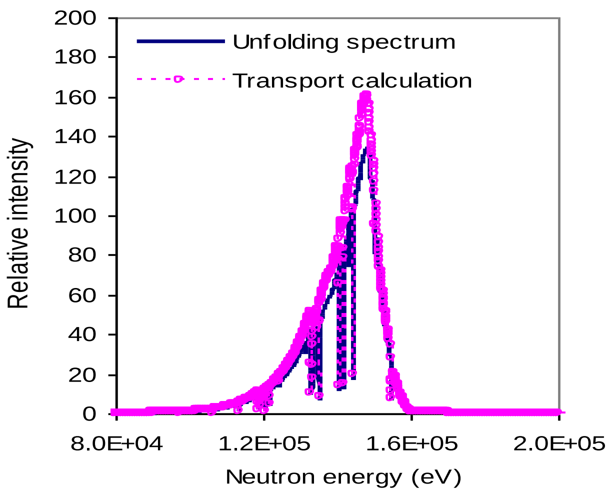

Fig. 3. Energy spectrum of the 148keV neutron beam at the channel No.4 of DNRR

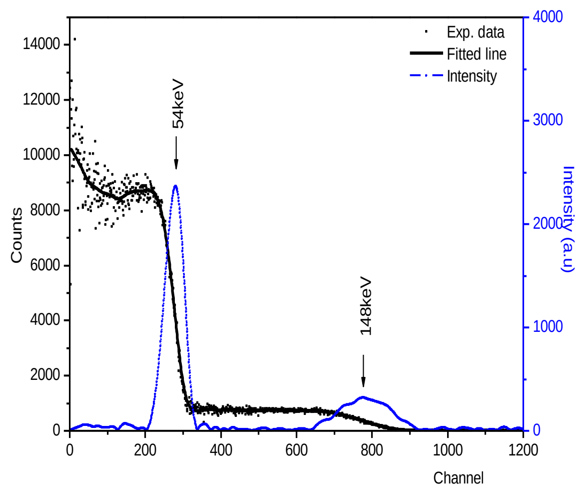

Fig. 4. Measured energy spectrum of the 54keV neutron beam at the channel No. 4 of DNRR

The neutron beams of 24keV, 59keV and 133keV:

As progressive necessary of reactor based mono-energetic neutron beam lines for experimental researches on neutron interaction with mater, the new three filtered neutron beam of 24keV, 59keV and 133keV have been developed and applied from 2008 [3] based on the neutron source from the channel No. 4 of DRR. The characteristics of these neutron beam lines are introduced in the references [6, 7], and summarized in Table II. The calculated and measured energy spectra of these neutron beam lines are shown in Figs. 5-7.

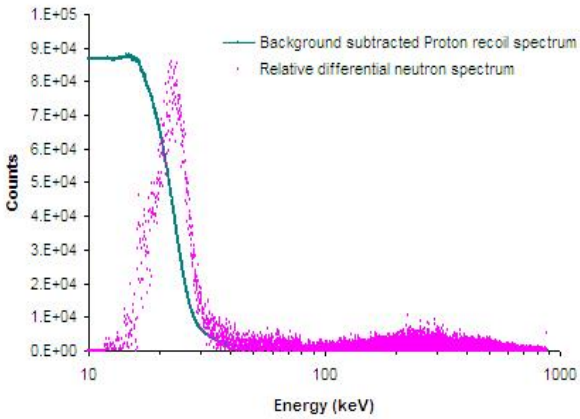

Fig. 5. Measured neutron spectrum for 24keV beam by proton recoil proportional counter

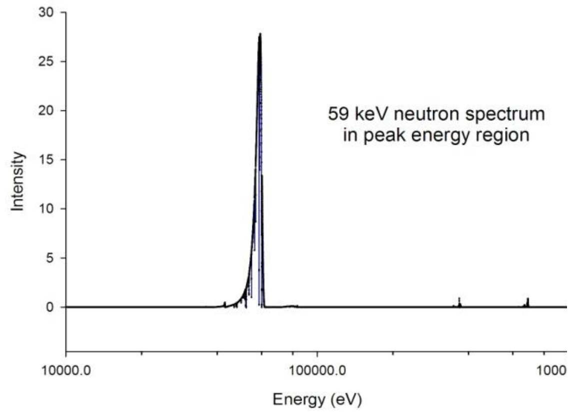

Fig. 6. Calculated neutron spectrum for the 59keV filtered neutron beam

Table II. Characteristics of the 24keV, 59keV and 133keV neutron beams at the channel No.4

Parameters	**24keV**	**59keV**	**133keV**
Neutron flux (n/cm^2.s)	6.1x10^5	5.3x10^5	3.2x10^5
Energy resolution (keV)	1.8	2.7	3.0
Peak relative intensity (%)	96.72	92.28	92.89
Beam collimated diameter (cm)	3	3	3
Composition of Filters	B 0.2g/cm^2 Fe 20cm Al 30cm S 35g/cm^2	B 0.2g/cm^2 Ni 10cm V 15cm Al 5cm S 35g/cm^2	B 0.2g/cm^2 Cr 50g/cm^2 Ni 10cm Si 60cm

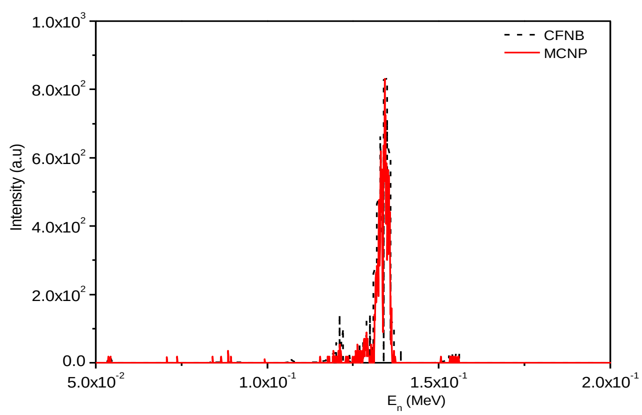

Fig. 7. Calculated neutron spectrum for the 133keV filtered neutron beam

III. NUCLEAR DATA MESUREMENTS

Neutron capture cross section measurements:

The measurements of neutron capture cross sections for a number of nuclides have been performed on the filtered neutron beams with mono-energies of 24, 54, 59, 133 and 148 keV, at the Dalat nuclear research reactor. The measured neutron capture cross sections data were obtained relative to the standard capture cross sections of the $^{197}Au(n,\gamma)^{198}Au$ reaction by the activation method. An abridged description of data analysis procedure is presented as follows:

The average capture cross sections, $<\sigma_a>^x$, for nuclide x at average neutron spectrum $<\Phi>$ can be determined relative to that of ^{197}Au standard by the following relations:

$$<\sigma_a> = \frac{C^x f(\lambda,t)^x f_c^x I_\gamma^{Au} \varepsilon_\gamma^{Au} N^{Au} <\sigma_a>^{Au}}{C^{Au} f(\lambda,t)^{Au} f_c^{Au} I_\gamma^x \varepsilon_\gamma^x N^x}; \quad (2)$$

$$f(\lambda,t) = \frac{\lambda}{(1-e^{-\lambda t_1})e^{-\lambda t_2}(1-e^{-\lambda t_3})}, \quad (3)$$

where the superscript 'x' denotes sample nucleus, and 'Au' denotes the reference nucleus ^{197}Au. 'C' stands for net counts of the corresponding gamma peak. 't_1', 't_2' and 't_3' are irradiating, cooling and measuring times, respectively. 'λ' is decay constant of the product nucleus; 'ε_γ' is the detection efficiency of detector; 'I_γ' is the intensity of interesting γ-ray, and 'f_c' is the correction factor for self-shielding multiple scattering effects that can be exactly calculated by the Monte Carlo method.

In recent years, we have conducted a series of cross section measurements for neutron capture (n, γ) reactions in different nuclides, and reported in scientific papers such as: ^{109}Ag, ^{186}W, ^{158}Gd [8]; ^{139}La, ^{152}Sm, ^{191}Ir, ^{193}Ir [9]; ^{185}Re and ^{187}Re [10, 11]. In addition, the horizontal thermal Column of DNRR, a well thermalized neutron channel, has been also used for measurement of thermal neutron capture cross section and resonance integral of ^{69}Ga and ^{71}Ga [12]. A typical result of our measurements in comparison with data from other laboratories is shown in Fig. 7 [10].

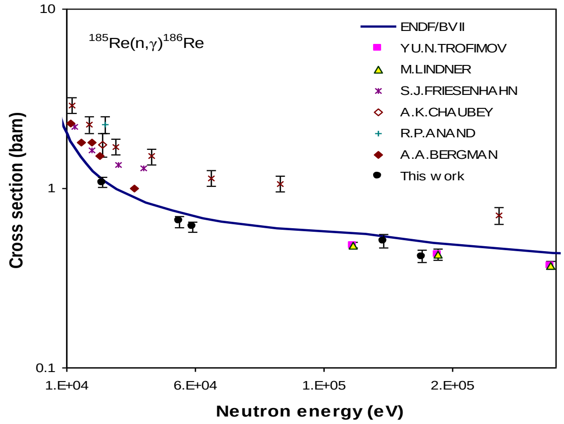

Fig. 7. Neutron capture cross section of ^{185}Re [10]

Measurements of neutron total cross sections:

The total neutron cross section measurements are being carried out by the transmission method for natural elements of U, C, Fe and Al, at the filtered neutron energies of 24keV, 54keV, 59keV, 133keV and 148keV. The experimental value of neutron total cross section, σ_t, can be exactly determined from the following expression:

$$\sigma_t = \frac{1}{\rho d}\ln\left(\frac{1}{T}\right) = \frac{1}{\rho d}\ln\left(\frac{\Phi_0}{\Phi}\right), \quad (4)$$

where 'T' is transmission coefficient of the collimated neutron beam that transmitted through a purity sample with thickness d (cm); 'ρ' denotes density of the sample (Atom/cm^3). 'Φ_0' and 'Φ' are measured neutron fluxes at before and after positions of the irradiating sample, respectively. A measurement of the transmission spectrum for

54keV neutron beam at the channel No.4 of DNRR is shown in Fig.8.

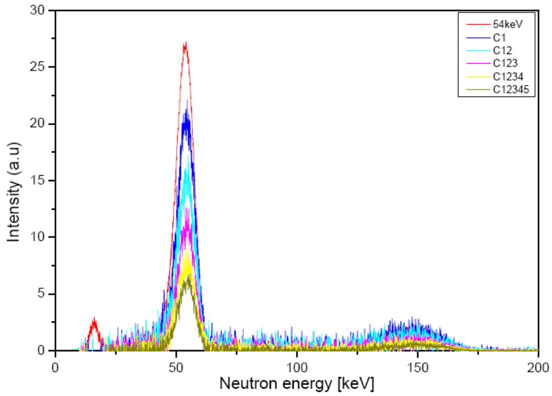

Fig. 8. Measured neutron spectrum of 54keV neutron beam transmitted through different thickness of C sample.

IV. PGNAA APLICATIONS

From 1998, the 148keV filtered neutron beam at the channel No.4 has been applied for possibility studies the method of in-vivo prompt gamma neutron activation analysis (IVPGNAA) that involves the exposure of the living human organs to a small dose of neutrons. At that time, IVPGNAA is a new technique for directly determination of toxic elements accommodated in a specific living human organ such as concentrations of Hg in kidney and Cd in liver. The research was carried out on a physical phantom installed at the channel No.4 [13]. The results given from this investigation introduced a high effective new experiment with 148keV neutron beam instead of thermal neutrons [13].

The low background and well thermal filtered neutron beam from the channel No.2 [4] of Dalat nuclear research reactor is an advantage neutron source for prompt gamma-ray neutron activation analysis (PGNAA). Accordingly, a modern Compton suppression PGNAA spectroscopy used a compact system of BGO-HPGe detectors was completely developed and installed at the experimental space of this beam port, from 2012. A preliminary study on calibration and analytical sensitivity for several domination elements has been conducted. A prompt gamma-ray spectrum of geometrical sample measured in single and Compton-suppression modes is shown in Fig.9. The results in this study allows us to estimate that the new PGNAA facility installed at the channel No.2 of DNRR is qualified to participate in analytical services at the Institute. A calibration curve for Boron analysis is presented in Fig.10, and the results of comparison analysis used standard soil sample (NIST-2711a) is given in Table III.

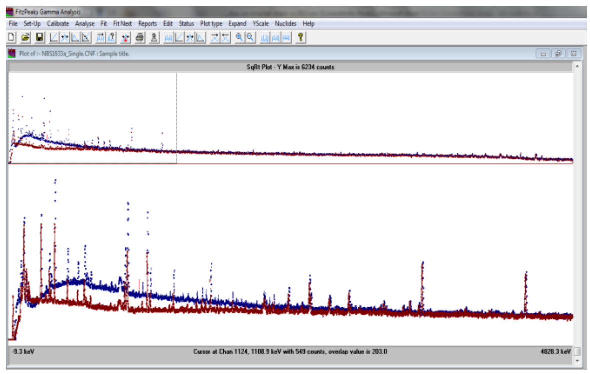

Fig. 9. Prompt gamma-rays spectrum measured at the thermal neutron beam No.2 for soil sample, in single and Compton-suppression modes.

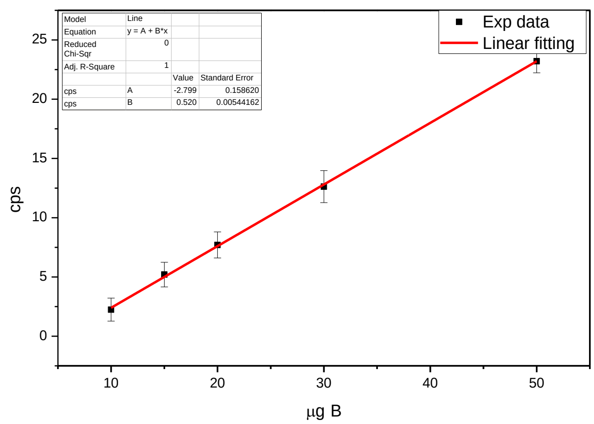

Fig. 10. The calibration curve for Boron analysis by using the PGNAA facility at the channel No.2

Table III. The results of comparison analysis used the standard soil sample (NIST-2711a), by using the PGNAA facility at the channel No.2

Sample	NIST-2711a *(Standard sample: Montana soil)*	
Elements	Measured values	Reference values
B (μg/g)	50.5 ± 2.9	50
Gd (μg/g)	7.59 ± 3.34	5
Sm (μg/g)	6.96 ± 1.07	5.93 ± 0.28
Ca (%)	2.43 ± 0.59	2.42 ± 0.06
Al (%)	7.1 ± 0.3	6.72 ± 0.06
Si (%)	31.66 ± 3.93	31.4 ± 0.7
K (%)	2.39 ± 0.28	2.53 ± 0.10
Ti (%)	0.29 ± 0.06	0.32 ± 0.01
Na (%)	2.02 ± 0.48	1.20 ± 0.01
Fe (%)	3.01 ± 0.35	2.82 ± 0.04

V. CONCLUSIONS

The accomplishment of research activities on the topics of filtered neutron beams development and it’s applications based on the neutron sources from the horizontal channel No.2 and No.4 of Dalat nuclear research reactor is reviewed in this report. The neutron filter technique has been effectively applied to provide mono-energetic neutron beam lines with qualified characteristics for related applications at the Nuclear Research Institute, VINATOM. The basis researches on experimental neutron induce nuclear reaction cross sections conducted by using these neutron beams have been performed with interesting results, and this research activity is proposed to be continued, in order to participate in providing of precise experimental nuclear reaction data and educational experiments. The new PGNAA facility installed coupling with the well thermal neutron beam at the channel No.2 plays as an important application of this channel for studies on neutron capture experiments and elemental analysis. This will be an important supplementation to the neutron activation analysis (NAA) method at the Dalat research reactor.

The new development of neutron beam with possible mono-energy of 2keV, and extension of application studies such as Boron neutron capture therapy (BNCT) and neutron dosimeter calibration are proposed.

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