

Modeling of Filters for Formation of Mono-Energetic Neutron Beams in the Research Reactor IRT MEPhI

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ABSTRACT: The paper considers formation of mono-energetic neutron beams at the entrance of experimental channels in research reactors for various applications. The problem includes the following steps:

1. Full-scale mathematical model of the research IRT MEPhI was developed for numerical evaluations of neutron spectra and neutron spatial distribution in the area of experimental channels.
2. Modeling of filters in the channel to shift neutron spectrum towards the required mono-energetic line was performed.
3. Some characteristics of neutron beams at the entrance of experimental channel with the filter were evaluated.

The filter materials were selected. The calculations were carried out with application of the computer code based on the high-precision Monte-Carlo code MCNP. As a result, mathematical model was created for the filter which is able to form mono-energetic (24 keV) neutron beam. The study was carried out within the frames of the research project on development of Russian emission detector with liquid noble gas to observe rare processes of neutrino scattering and particles of hypothetical dark matter in atomic nuclei.

KEYWORDS: neutron filter, MCNP, Monte-Carlo, total cross-section, background, radiation shielding, detector

I. INTRODUCTION

The paper presents the technique needed to resolve the problem related with formation of quasi-monochromatic neutron beams for experimental observation of some rare processes including coherent scattering of antineutrinos on a heavy atomic nucleus when recoil nuclei with energies at the level of several hundreds electron-volts should be detected and for experimental search for the Dark Matter particles with application of detectors filled up with liquid noble gases. It was supposed to use the emission two-phase noble-gas detector with electroluminescent strengthening which allows to detect an extremely small ionization value – up to one electron [1].

This detector can be used to register coherent scattering of the reactor antineutrinos with cross-sections by tens times higher than cross-sections of inverse beta-decay which is often used to detect neutrinos [2, 3]. However, planning of such an experiment is impossible without available information about ionization and scintillation yields from the tracks of recoil xenon nuclei with energies below 1 keV.

The planned experiment will investigate the response of the liquid-xenon emission detector in the sub-keV energy range for recoil xenon nuclei at elastic scattering of a quasi-monochromatic neutron beam extracted from a continuous spectrum of the reactor neutrons with application of composite interferential filters.

II. MODELING FILTER

Currently, experimental installation is mounted in horizontal experimental channel GECh-10 of the research reactor IRT MEPhI with thermal power of 2.5 MW (Figure 1). Quasi-monochromatic neutron beams will be formed by the composite interferential filters composed of elemental pairs, where one isotope has a deep interference minimum in total cross-section while other isotopes can effectively suppress transmission in other energy ranges. For example, the filter composed of 30-cm ⁵⁶Fe and 100-cm ²⁷Al can cut out the 24-keV peak with width of 2.5 keV from quasi-continuous neutron spectrum. The peaks with energy 54 ± 1.5 keV, 149 ± 7 keV and 275 ± 12 keV [4, 5] can be formed by proper selecting thickness of the absorbing pairs Si-Ti and Mn-V-S.

Neutron transport from the reactor core through GECh-10 to the filter area was modeled by the computer code MCNP-A [6]. Calculations were carried out in two stages due to the great relaxation of neutron flux. At the first phase, neutron spectra and angular distributions in horizontal experimental channel GECh-10 were studied. At the second phase, neutron fluxes passing through GECh-10 and the filters were calculated. The normalization of the results to the actual thermal power of the reactor allowed us to evaluate absolute values of monochromatic neutron flux. These data will also be used to optimize passive radiation shielding of the detector.

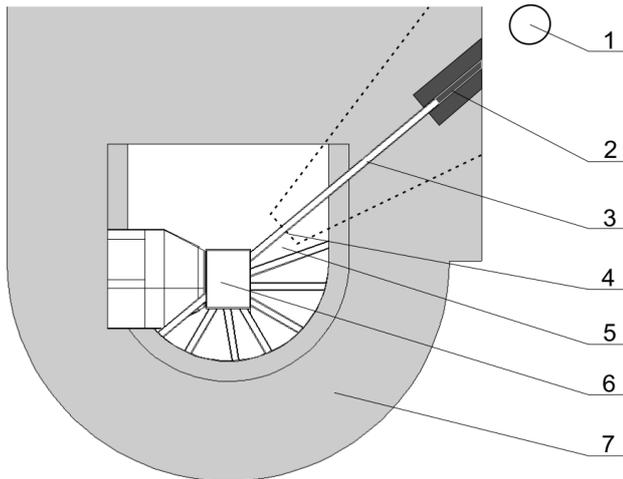


Fig. 1. Arrangement of the detector in the research reactor IRT MEPhI:

1 – detector; 2 – interferential filter; 3 – horizontal channel GECh-10; 4 – the surface for description of neutron source; 5 – water around the reactor core; 6 – the reactor core; 7 – reinforced radiation shielding of the reactor core (radial thickness – 1.5 m).

1. Neutron spectrum and angular distribution

Full-scale mathematical model of the research reactor IRT MEPhI was developed to simulate a real neutron spectra and angular distributions. The calculations were carried out with application of the card KCODE for detailed description of neutron source in experimental channel GECh-10. This surface was used in the calculations to choose optimal design of the filter and to obtain full information about the channel including its environment and radiation shielding of the detector.

2. Determination of the filter materials

The wide set of natural elements and high-purity isotopes were used as components for the neutron filters. The following natural elements and high-purity isotopes were analyzed: Si, Al, V, Sc, S, Mn, Fe, Ti, Mg, Co, Ce, Cr, Rh, Cu, B, Cd, LiF; ^{52}Cr (99.3%), ^{54}Fe (99.92%), ^{56}Fe (99.5%), ^{57}Fe (99.1%), ^{58}Ni (99.3%), ^{60}Ni (92.8-99.8%), ^{62}Ni (98.0%), ^{80}Se (99.2%), ^{10}B (85%), ^7Li (90%). The use of these materials makes variation of the filter parameters (purity, intensity, width) [4] possible.

The materials can be divided into the following groups:

- light elements – boron (B), lithium (Li), fluorine (F), i.e. neutron absorbers in (n, α) and (n,T) reactions
- medium elements – silicon (Si), aluminum (Al), vanadium (V), scandium (Sc), sulfur (S), manganese (Mn), iron (Fe), titanium (Ti), magnesium (Mg), cobalt (Co), i.e. materials with resonances of cross-sections in the energy range of 10 keV – 1 MeV. Thickness of the filter materials can be varied to get a compromise between the spectral quality, the incident intensity and the signal-to-background ratio.

- heavy elements – cadmium (Cd), cerium (Ce), ruthenium (Ru), i.e. neutron absorbers mainly in (n, γ) reaction with resonances of radiative capture cross-sections in thermal energy range.

Iron was chosen as a main component of the filter for the planned experiment because iron has an interferential minimum of total cross-section in the vicinity of 24 keV. Aluminum was chosen as an additional material because aluminum has resonance peaks in its cross-section at energies above 24 keV, that allows to «cut» out the neutrons that passed through the less deep interferential minima of iron from neutron spectrum. Total cross-sections of these materials are shown in Fig. 4.

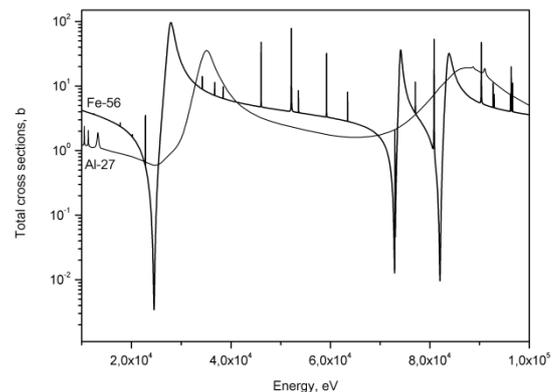


Fig. 4. Total cross sections of ^{56}Fe and ^{27}Al

The use of ST3 steel instead of isotope ^{56}Fe leads to the lower values of transmission coefficient for quasi mono-energetic neutron beam after the filter and worsens signal-to-background ratio.

3. Calculations of the filter characteristics

Thermal power of the research reactor IRT MEPhI is equal to 2.5 MW. As is known, about 200 MeV is released in one fission reaction, or $3.2 \cdot 10^{-11}$ J per a fission. Defining the number of fissions per second as a thermal power, divided by the energy yield of a fission reaction, we get the value of $7.8 \cdot 10^{16}$ fissions a second. Considering the average number of secondary fission neutrons as $\nu = 2.5$, we determine the total number of neutrons per time unit as $2.0 \cdot 10^{17}$ n/sec.

Full neutron current with energies below 15 MeV through the surface of neutron source obtained in calculations of full-scale IRT MEPhI model is equal to 10^{14} n/sec. Neutron source for the filter calculations is formed on this surface. Neutron current along the channel axis within 1-degree solid angle through the surface is equal to $3.7 \cdot 10^{10}$ n/sec.

Neutron current of neutrons with energies from 20 keV to 25 keV at the output of the filter-free GECh-10 channel within 1-degree solid angle is equal to $2.2 \cdot 10^7$ n/sec.

Calculations were carried out with different thickness of the selected materials (steel and aluminum). The calculated values of neutron transmission coefficient and signal-to-background ratio are shown in Fig. 5 and 6,

respectively, for aluminum.

Analysis of neutron transmission coefficient and signal-to-background ratio allowed us to select the filter based on 100-cm Al and 30-cm ST3 steel. Neutron current with energies from 20 keV to 25 keV in this filter at the output is equal to $7 \cdot 10^4$ n/sec, and signal-to-background ratio is equal to about 40. If isotope ^{56}Fe is used instead of ST3 steel, then neutron current of neutrons is equal to $3.15 \cdot 10^5$ n/sec, and signal-to-background ratio is equal to about 44.

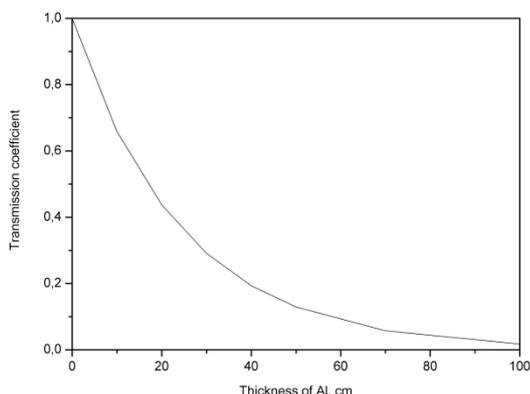


Fig. 5. Transmission coefficient

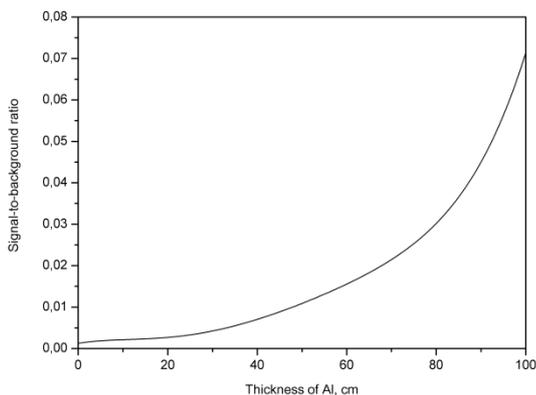


Fig. 6. Signal-to-background ratio

III. SIMULATION OF EXPERIMENTAL CHANNEL WITH RADIATION SHIELDING OF THE DETECTOR

Neutron and gamma-ray background has a strong influence on quality of the experiment. It is necessary to protect the detector from the effects caused by radiation background. Some possible options for radiation protection of experimental channels as well as radiation protection of the detector were analyzed. The model of experimental channel with its radiation shielding is shown in Fig. 7.

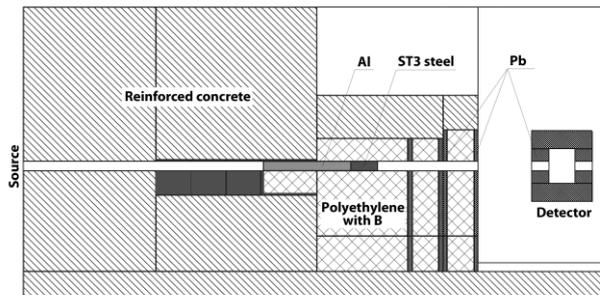


Fig. 7. Experimental channel with radiation shielding

Radiation shielding of experimental channel is presented as an iron damper filled up with plates of borated polyethylene (5 cm thick each), and the movable structure consisted of borated polyethylene and lead plates.

Calculations were carried out for models of GECh-10 channel with real geometries of the environment: without any radiation shielding, radiation shielding of GECh-10 channel only, radiation shielding of GECh-10 channel and the detector. The calculated values of signal-to-background ratio are shown in Table 1.

Table 1. Values of signal-to-background ratio

Models of GECh-10 channel with real geometries of the environment:	Signal-to-background ratio
without any radiation shielding	0.01
with radiation shielding of the channel only	39.10
with radiation shielding of the channel and the detector	34.10

Radiation shielding of the detector is a cylindrical lead layer with hole for neutron beam, closed from above and below by lead discs.

IV. CONCLUSIONS

This work confirmed again the possibility of obtaining quasi-monochromatic neutron beams at the output of experimental channels in the research reactor.

Simulated filter with radiation shielding of the detector made it possible to form a quasi-monochromatic neutron beam with energy of 24 keV at the output of experimental channel in the research reactor IRT MEPhI.

Information about radiation background for the reactor in operation is required for further optimization of radiation shielding and for upgrading accuracy in parameters of neutron beam incident on the detector.

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