Раздел четвертый

ДИАГНОСТИКА И МЕТОДЫ ИССЛЕДОВАНИЙ

REGISTRATION OF THE THERMAL NEUTRONS USING UNCOOLED Si PLANAR DETECTOR

G.L. Bochek, O.S. Deiev, S.K. Kiprich, N.I. Maslov,
M.Y. Shulika, G.P. Vasiliev, V.I. Yalovenko
National Science Center “Kharkov Institute of Physics and Technology”, Kharkov, Ukraine

The registration of thermal neutrons by Si planar detector with natural metallic Gd neutron converter was performed. The ^{239}Pu-Be(α, n) fast neutron source with flux $1.13 \cdot 10^5$ c^{-1} with paraffin moderator for obtaining of thermal neutrons was used. Control measurements of the thermal neutron flux by detector-dosimeter MKS-01R were performed. Experimental spectra for the reaction Gd(n, γ)Gd were measured. Spectra consisted of the spectra conversion electrons in energy range 30…200 keV with maximum at energy ~ 70 keV and Gd CXR lines. Background gamma-radiation was measured by Si PIN detector without Gd plate. Program code GEANT4 for the calculation of the thermal neutron flux was used.

PACS: 28.20.Gd, 07.05.Tp

INTRODUCTION

Semiconductor neutron detectors based on thin-film coatings of neutron active material (converter foils) close to surface semiconductor diode used for the detection of neutrons. The using Gd foil and conversion electrons from the reaction Gd(n, γ)Gd were experimentally and theoretically studied in [1–5]. Experiments in this direction also carried in NSC KIPT [6, 7].

Purpose of the present work – the development and testing of a small-size single-channel detection modules thermal neutrons based on planar Si uncooled detector and metal Gd converter [8]. Detectors with an area of 2x2; 5x5 mm and a thickness of 0.3 mm were used. The detector sensitivity and spatial resolution defined by dimensions of detectors. We supposed to measure the minimal neutron flux up to 1 neutron per sec. For this work spectrometric equipment was available, including the required amount of Si uncooled detectors developed in NSC KIPT [9, 10], with good energy resolution (FWHM ~ 0.9 keV).

THE EXPERIMENTAL TECHNIQUE

Gadolinium has the largest cross section of thermal neutron capture (up to 300000 Barn) [2, 3]. Natural gadolinium contains two important isotope ^{155}Gd – 14.8% (cross section 17000 Barn), ^{157}Gd – 15.7% (cross section 300 000 Barn).

Neutron capture reactions with a maximum cross section:

$n + {}^{155}Gd \to {}^{156}Gd^* \to {}^{156}Gd + \gamma$-quanta + Gd CXR + conversion e^- (39…199 keV);

$n + {}^{157}Gd \to {}^{158}Gd^* \to {}^{158}Gd + \gamma$-quanta + Gd CXR + conversion e^- (29…182 keV).

In this paper, we registered the Gd CXR lines with energy $K_\alpha = 42.99$ and $K_\beta = 48.69$ keV and conversion electrons in energy range 30…200 keV.

The ^{239}Pu-Be(α, n) fast neutron source with flux $1.13 \cdot 10^5$ c^{-1} with paraffin moderator for obtaining of thermal neutrons was used.

We used the gadolinium foil of 0.4 mm which was placed on the Si detector (Fig. 1) [8].

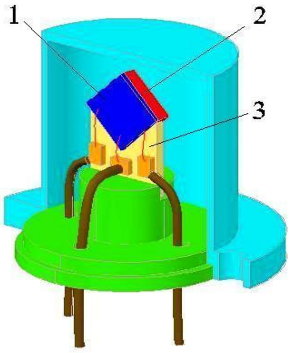


Fig. 1. Schematic drawing of the sealed module for thermal neutrons detection: 1 – Si planar detector; 2 – gadolinium converter; 3 – dielectric holder of a detector

The experimental scheme is shown in Fig. 2. The thickness of paraffin around the Si detector and the ^{239}Pu-Be(α, n) neutron source was 10 cm. Experimental scheme in the figure is not to scale.

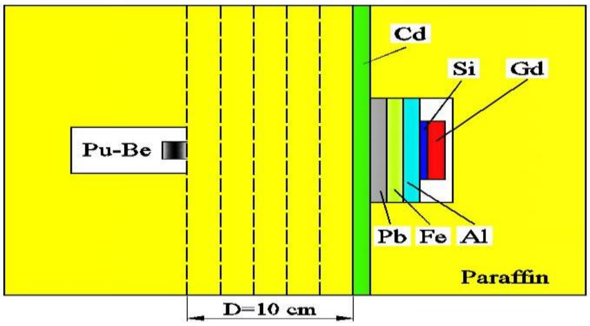


Fig. 2. Experimental scheme

The paraffin thickness between the detector and neutron source could vary from 0 to 10 cm. Distance between the detector and the neutron source respectively was 0…10 cm (*D*, cm). Lead foil (0.2…2 cm), Fe (15 mm), Al (1 mm) for the cut-off gamma background was applied. Cd foil (0.8 mm) for thermal neutron absorption was used. The presence or absence of paraffin over the source (left) changes the number of thermal neutrons up to 2.5 times.

Fig. 3 shows preamplifier (2×2×6 cm), detection module, which was placed inside the paraffin and the power supply (outside paraffin).

Fig. 3. Experimental setup used in Gd measurements: 1 – detection module; 2 – preamplifier (2×2×6 cm), and 3 – the power supply

To control the thermal neutron flux used industrial detector dosimeter MKS-01R. The typical thermal neutron flux in experiment ~ 30 $n \cdot cm^2 \cdot s^{-1}$, i.e. less than 1 neutron per second to area Si detector (2x2 mm).

Background of thermal neutrons for the $E_n < 0.025$ eV was ~ 0.01 $n \cdot cm^2 \cdot s^{-1}$ (without ^{239}Pu-Be(α, n)).

Gamma-ray spectra from ^{239}Pu-Be(α, n) source were measured for different experimental conditions. Evaluation of gamma background in the silicon detector was performed. The sources ^{241}Am, activity ~ 8E+6 Bq and ^{239}Pu-Be(α, n) alternately close to Si detector were placed (Fig. 4).

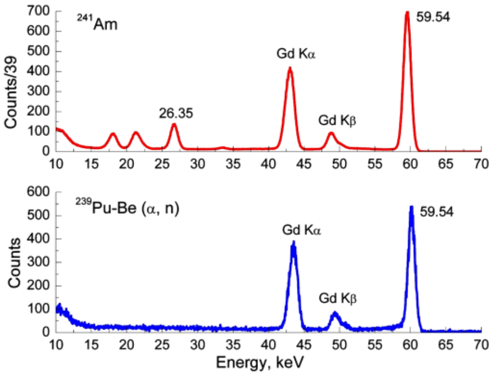


Fig. 4. Gamma-spectra for sources ^{241}Am (red color) and ^{239}Pu-Be(α, n) (blue color)

In both cases clearly visible line with energy 59.54 keV (channel ~ 1400) and gadolinium CXR excited by this line 59.54 keV (channel ~ 1000, 1100). According to estimates, PuBe source gives gamma line with energy 59.54 keV ~ 1.6E+5 Bq. This is a serious source of background in the silicon detector. Lead foil (0.2…2 cm), Fe (15 mm), Al (1 mm) for the cut-off gamma-background was applied in experiment.

COMPUTER SIMULATION

GEANT4 simulation toolkit and PhysList QHSP_BIC_HP for simulate neutron transport and scattering was used [11, 12].

Primary neutron spectrum was modeled similar spectra of ^{239}Pu-Be(α, n) neutron source [13] (Fig. 5).

The energy distribution of the thermal neutrons corresponds to the known Maxwell curve with a maximum of $kT \sim 0.025$ eV (Fig. 6). As follows from calculations number neutrons of $E_n < 0.025$ eV is equal ~ 0.25 number neutrons of $E_n < 0.1$ eV.

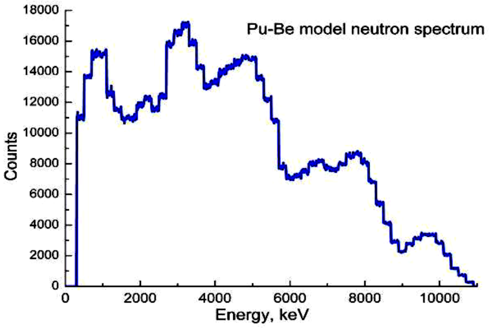


Fig. 5. Primary neutron spectrum modeled similar spectrum of ^{239}Pu-Be(α, n) neutron source [12]

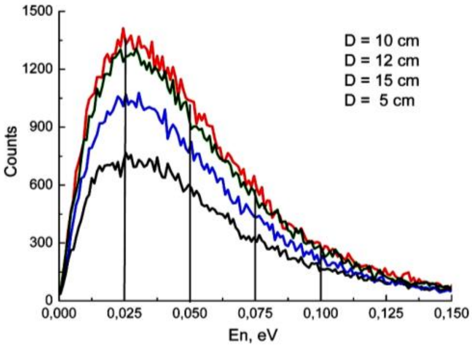


Fig. 6. The energy distribution of the thermal neutron after passing through a layer of paraffin

We note that industrial device MKS-01R measures neutrons with energy $E_n < 0.025$ eV. Respectively, for the $E_n < 0.1$ eV experimental neutron number should be multiplied by about 4 (see Fig. 6). Thus the approximate thermal neutron flux was estimated.

The calculated spectra of conversion electrons to estimate the experimental results were used [3, 12].

Conversion electrons of Gd(n, γ) reaction for natural Gd were calculated in GEANT4.

The Gd(n, γ)Gd reaction in natural Gd produces a quite complex conversion electron spectra (Figs. 7–9) with significant energy lines between 29 and about 200 keV.

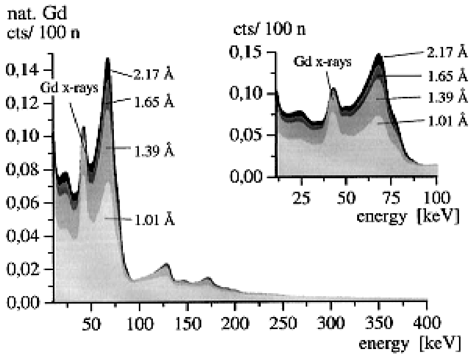


Fig. 7. Spectra of the reaction products of the neutron capture in natural Gd for different neutron wavelengths, as seen in a Si planar detector (300 μm) in backward direction [3]

Note, neutron wavelengths 1 A – E_n= 0.08 eV, σ = 13000 Barn (^{157}Gd); 1.8 A – 0.025 eV, σ = 48000 Barn; 3 A – 0.009 eV, σ = 70000 Barn; 4A – 0.005 eV, σ = 89000 Barn.

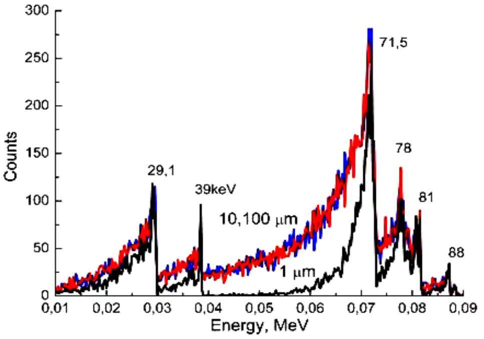


Fig. 8. Spectra of the conversion electrons of the neutron capture in natural Gd for different thicknesses of Gd (μm: 1 – black color, 10 – red, 100 – blue), in Si planar detector (300 μm) in backward direction (E_n = 0.0025 eV)

Yield of the conversion electrons of about 11 on 100 neutrons (E_n = 0.025 eV) for natural Gd thickness greater than 10 μm (natural Gd).

Fig. 9 shows our calculations conversion electrons, passed through the passive protective layer of detector. As can be seen, fine structure is hidden and the electrons peak position is shifted to lower energies.

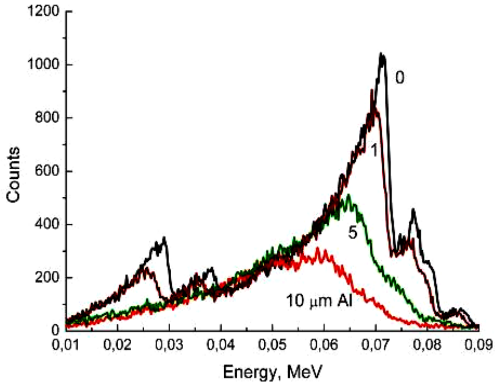


Fig. 9. Calculations conversion electrons, passed through the passive protective layer (Al) thickness of 0, 1, 5, and 10 μm

RESULTS AND DISCUSSION

EXPERIMENT WITH Cd FOIL

Fig. 10 shows the experimental spectrum of the conversion electrons and CXR Gd of the neutron capture in natural Gd in a Si-planar detector (2×2×0.3 mm) in backward direction. Experimental spectrum has similar form with the calculated spectrum in Fig. 7. Cadmium foil is absent.

Figs. 11 and 12 shows the experimental spectrum of the conversion electrons and CXR Gd in a Si planar detector (2×2×0.3 mm) in backward direction.

Spectra were measured with and without cadmium foil before the detector. As can be seen (see Figs. 11, 12), in the spectra appear an additional peak in the energy range 50…85 keV, a maximum of ~ 70 keV. This is conversion electrons.

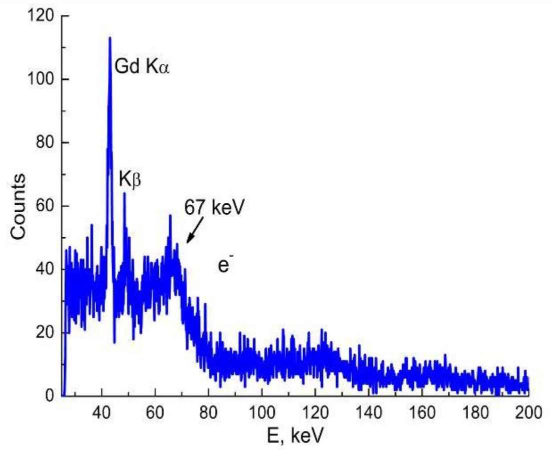
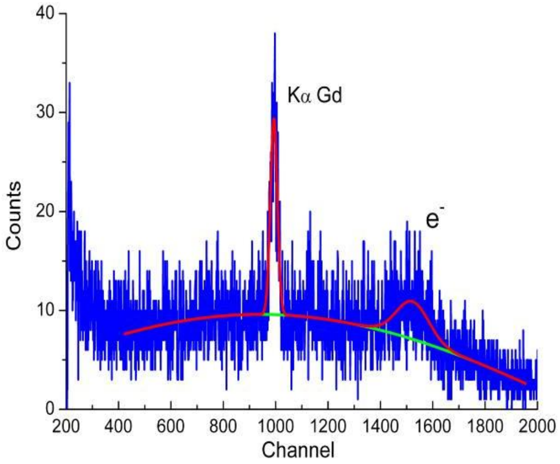
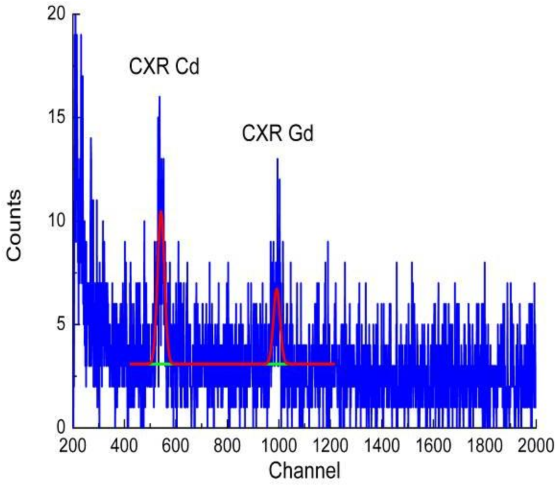


Fig. 10. Experimental spectrum of the conversion electrons and CXR Gd of the neutron capture in natural Gd in a Si planar detector (2×2×0.3 mm) in backward direction. D = 10 cm, foil Pb = 22 mm, Fe = 15 mm, Al = 1 mm

Cd foil totally cut off a thermal neutrons, but line CXR Cd in the presence of cadmium foil remains. Consequently, CXR Gd excited not only by neutrons, quanta CXR will be greater than expected by e-conversion.

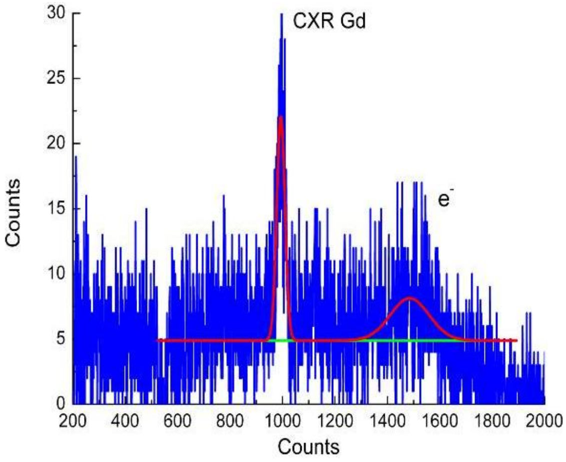


a – without cadmium foil



b – detector closed by cadmium foil

Fig. 11. Experimental spectra for the Si detector with metallic Gd (2×2 mm). D = 10 cm, Pb = 2 mm, Fe = 15 mm, Al = 1 mm



c – the result of subtracting the spectra a – spectra b

Fig. 11. Experimental spectra for the Si detector with metallic Gd (2×2 mm). D = 10 cm, Pb = 2 mm, Fe = 15 mm, Al = 1 mm

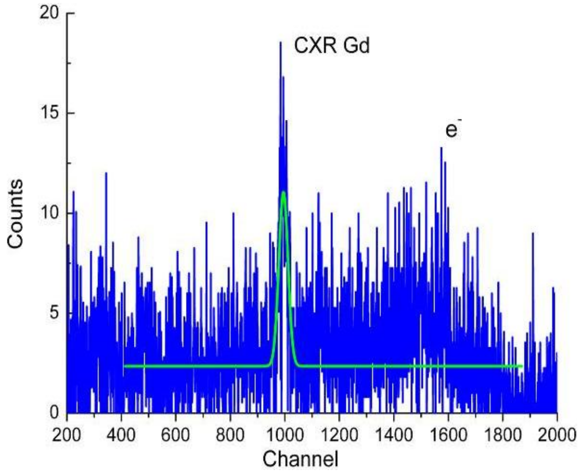


Fig. 12. Experimental spectra for the Si detector with metallic Gd (2×2 mm). Spectrum – the result of subtracting two spectra (with and without cadmium foil). D = 10 cm, Pb = 20 mm, Fe = 15 mm, Al = 1 mm

EXPERIMENT WITH PRESENCE AND ABSENCE Gd CONVERTER

To increase the number of detected neutrons, we used Si detector (5×5×0.3 mm) and Gd (5×5×0.3 mm). Effectiveness neutron detection increased in proportion of area detectors: 25/4 mm^2 about 6 times. The size of the detection module practically unchanged.

Fig. 13 shows the experimental spectrum of the conversion electrons and CXR Gd for different values of the thickness of paraffin *D* in the interval 0…10 cm (see Fig. 2). In this experiments layers Pb = 2 mm, Fe = 15 mm, Al = 1 mm applied to the cut-off this gamma background.

Fig. 14 shows the experimental spectrum of the background for different values of the thickness of paraffin *D* in the interval 0…10 cm. Gadolinium foil was removed. Experimental conditions in the presence and absence of Gd foil were the same.

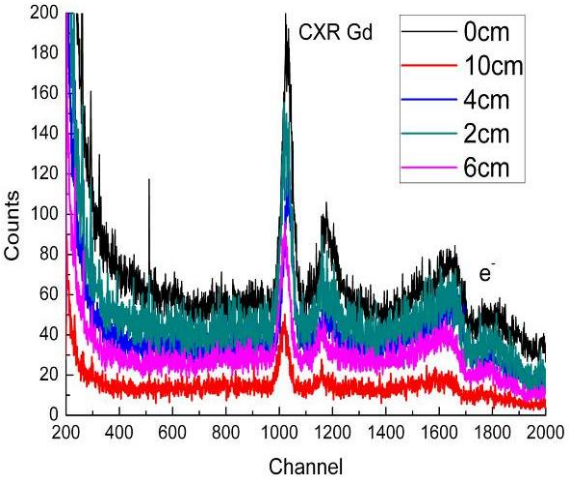


Fig. 13. Experimental spectrum of the conversion electrons and CXR Gd for different values of the thickness of paraffin D in the interval 0…10 cm. Pb = 2 mm, Fe = 15 mm, Al = 1 mm

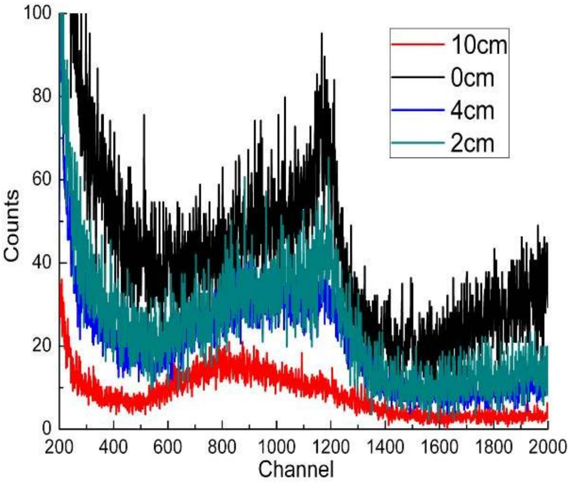


Fig. 14. Experimental spectrum of the background for different values of the thickness of paraffin D in the interval 0…10 cm. Gadolinium foil was removed. Pb = 2 mm, Fe = 15 mm, Al = 1 mm

Figs. 15 and 16 show the experimental spectra after background subtraction.

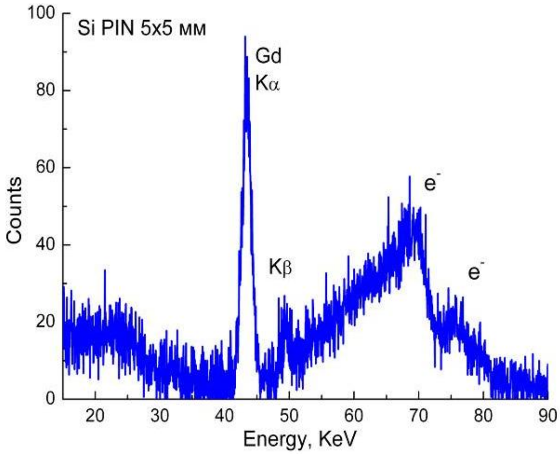


Fig. 15. Experimental spectra after background subtraction. D = 4 cm, Pb = 2 mm, Fe = 15 mm, Al = 1 mm

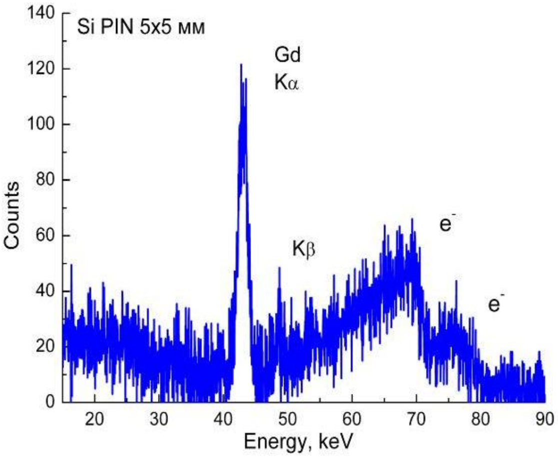


Fig. 16. Experimental spectra after background subtraction. D = 2 cm, Pb = 2 mm, Fe = 15mm, Al = 1 mm

The experimental result and calculations (see Figs. 8, 9) were compared.

Numerical estimates of conversion electrons in the energy range 50…85 keV, right after gadolinium CXR were performed. This interval is the most "low-background". Experimental thermal neutron flux was ~ 22 n·cm^2·c^{-1} in the case of paraffin $D = 10$ cm. MKS-01R gives neutron flux with $E_n < 0.1$ eV ~ 30 cm^2·c^{-1}. Similarly, for $D = 2$ cm paraffin neutron flux measured 75 cm^{-2}·c^{-1}, MKS-01R ~ 82 cm^{-2}·c^{-1}. Agreement is satisfactory.

CONCLUSIONS

Small-size single-channel detection modules thermal neutrons based on planar Si uncooled detector and metal Gd converter were developed and tested. Detectors with an area of 2x2, 5x5 mm and a thickness of 0.3 mm were used.

Experimental spectra for the reaction Gd(n, γ)Gd were measured. Spectra consisted of the Gd CXR lines with energy 42.99 and 48.69 keV and conversion electrons in energy range 30…200 keV with maximum at energy ~ 70 keV. Background were measured in two ways: 1 – Si detector without a layer of Gd; 2 – using Cd foil (cutoff thermal neutrons). Both methods gave similar results.

Registration and evaluation of the thermal neutron flux by the yield of internal conversion electrons were performed (selected range of 50…85 keV, where the background radiation were minimal for case 1 and 2).

Control measurements of the thermal neutron flux by detector-dosimeter MKS-01R were performed. Numerical estimates of the thermal neutron flux for Si detector were close to the results of the dosimeter MKS-01R.

Thus using planar Si uncooled detector and metal Gd converter experimental thermal neutron flux was determined.

REFERENCES

1. A. Foglio-Para, N.A. Gottardi, M. Mandelli Bettoni. Thermal neutrons Gd-detector // *Nucl. Instr. and Meth*. 1968, v. 65, issue 1, p. 110-112.

2. G. Bruckner, H. Rauch. A position sensitive Gd detector for thermal neutrons // *J. Nucl. Research*. 1996, v. 4, p. 141-147.

3. G. Bruckner, A. Czermak, H. Rauch, P. Weilhammer. Position sensitive detection of thermal neutrons with solid state detectors (Gd Si planar detectors) // *Nuclear Instruments and Methods in Physics Research A*. 1999, v. 424, p. 183-189.

4. M. Jamil, Hyun Yong Jo, J.T. Rhee, Y.J. Jeon. Simulation study using GEANT4 Monte Carlo code for a Gd-coated resistive plate chamber as a thermal neutron detector // *Radiation Measurements*. 2010, v. 45, issue 7, p. 840-843.

5. D.A. Abdushukurov, A.A. Dzhuraev, S.S. Evteeva, P.P. Kovalenko, V.A. Leskin, V.A. Nikolaev, R.F. Sirodzhi, F.B. Umarov. Model calculation of efficiency of gadolinium-based converters of thermal neutrons // *Nuc. Instr. and Meth. B*. 1994, v. 84, issue 3, p. 400-404.

6. G.L. Bochek, O.S. Deiev, N.I. Maslov, et al. Measurement of neutrons from ^{239}Pu-^{9}Be-source by Si-PIN-detector and converter layer GD$_2$O$_3$: *Abstr. of the 10th Conf. on High Energy Phys., Nucl. Phys. and Accelerators*, Feb. 27 – March 2, 2012, Kharkov, Ukraine. Kharkov: NSC KIPT, p. 96. http://kipt.kharkov.ua/ru/ihepnp_2012_tezis.html.

7. G.L. Bochek, O.S. Deiev, N.I. Maslov, et al. Registration of the thermal neutrons by Si PIN detector with Gd converter: *Abstr. of the XXIII International Workshop on Charged Particle Accelerators*, September 08–14, 2013, Ukraine, Alushta, the Crimea, p. 116. http://www.kipt.kharkov.ua/conferences/ihepnp/2013/iwcpa13/index.html.

8. G.P. Vasiliev, O.S. Deiev, S.K. Kiprich, et al. Module for thermal neutrons registration based on uncooled silicon detectors and metal gadolinium converter // *Problems of Atomic Science and Technology*. *Series "Nuclear Physics Investigations"*. 2016, N 3, p. 99-104.

9. G.P. Vasiliev, V.K. Voloshin, S.K. Kiprich, et al. Encapsulated modules of silicon detectors of ionizing radiation // *Problems of Atomic Science and Technology*. *Series "Nuclear Physics Investigations"*. 2010, N 3, p. 200-204.

10. G.L. Bochek, O.S. Deiev, N.I. Maslov, V.K. Voloshyn. X-ray lines relative intensity depending on detector efficiency, foils and cases thickness for primary and scattered spectra // *Problems of Atomic Science and Technology*. *Series "Nuclear Physics Investigations"*. 2011, N 3, p. 42-49.

11. Geant4: a toolkit for the simulation of the passage of particles through matter. CERN – the European Organization for Nuclear Research, 2011. http://www.geant4.org/geant4/

12. O.S. Deiev. GEANT4 simulation of neutron transport and scattering in media // *Problems of Atomic Science and Technology*. *Series "Nuclear Physics Investigations"*. 2013, N 3(85), p. 236-241.

13. M.E. Anderson, R.A. Neff. Neutron energy spectra of different size ^{239}Pu-Be(α, n) sources // *Nuclear Instruments and Methods*. 1972, v. 99, issue 2, p. 231-235.

Статья поступила в редакцию 20.05.2016 г.

РЕГИСТРАЦИЯ ТЕПЛОВЫХ НЕЙТРОНОВ С ПОМОЩЬЮ НЕОХЛАЖДАЕМОГО Si ПЛАНАРНОГО ДЕТЕКТОРА

Г.Л. Бочек, А.С. Деев, С.К. Киприч, Н.И. Маслов, М.Ю. Шулика, Г.П. Васильев, В.И. Яловенко

Выполнена регистрация тепловых нейтронов с помощью планарного Si-детектора с конвертором нейтронов из естественного металлического Gd. Для получения тепловых нейтронов использовался ^{239}Pu-Be(α, n)-источник быстрых нейтронов с потоком $1{,}13 \cdot 10^5$ c^{-1} с замедлителем из парафина. Контрольное измерение потока тепловых нейтронов выполнено с помощью детектора-дозиметра МКС-01Р. Измерен экспериментальный спектр реакции Gd(n, γ)Gd. Спектр состоял из электронов конверсии с энергией в диапазоне 30…200 кэВ, с максимумом при энергии ~ 70 кэВ и линий ХРИ Gd. Фоновое гамма-излучение измерено Si-детектором без слоя Gd. Программный код GEANT4 использован для расчета потока тепловых нейтронов.

РЕЄСТРАЦІЯ ТЕПЛОВИХ НЕЙТРОНІВ ЗА ДОПОМОГОЮ НЕОХОЛОДЖУВАНОГО Si ПЛАНАРНОГО ДЕТЕКТОРА

Г.Л. Бочек, О.С. Деєв, С.К. Киприч, М.І. Маслов, М.Ю. Шуліка, Г.П. Васильєв, В.І. Яловенко

Виконана реєстрація теплових нейтронів за допомогою планарного Si-детектора з конвертором нейтронів з природного металевого Gd . Для отримання теплових нейтронів використовувалося ^{239}Pu-Be(α, n)-джерело швидких нейтронів з потоком $1{,}13 \cdot 10^5$ c^{-1} зі сповільнювачем з парафіну. Контрольне вимірювання потоку теплових нейтронів виконано за допомогою детектора-дозиметра МКС-01Р. Виміряно експериментальний спектр реакції Gd(n, γ)Gd. Спектр складався з електронів конверсії з енергією в діапазоні 30...200 кеВ, з максимумом при енергії ~ 70 кеВ і ліній ХРІ Gd. Фонове гамма-випромінювання виміряно Si-детектором без шару Gd. Програмний код GEANT4 використано для розрахунку потоку теплових нейтронів.