DETECTORS AND NUCLEAR RADIATION DETECTION

TECHNIQUE OF THERMAL NEUTRONS REGISTRATION BY TWO-CHANNEL SPECTROMETRIC SYSTEM BASED ON UNCOOLED Si-DETECTORS AND GADOLINIUM CONVERTER

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A block diagram was developed and a working model of a small-sized two-channel spectrometric detection system for thermal neutrons registration was produced. The spectrometric system is created on the basis of silicon planar uncooled detectors and a metallic gadolinium converter. A method has been developed for measuring the thermal neutrons flux density (fluence) for use in nuclear physics and nuclear medicine. A two-detector spectrometric system based on planar Si detectors and Gd converters allows to register thermal neutrons by measuring the output of conversion electrons with the possibility of accounting of background radiation. The fast neutron source ^{239}Pu-Be (α, n) and the paraffin moderator were used in the experiments.

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INTRODUCTION

The detection of thermal neutrons by a spectrometric detection system based on silicon planar uncooled detectors (SPUD) and a converter from metallic gadolinium demands special requirements for the energy resolution, noise level and sensitivity of detectors, since the conversion electrons produced after neutron capture by gadolinium have a low energy [1].

To reach high electro-physical characteristics and high energy resolution of SPUD crucible-free zone melting was used to create high-resistance silicon, mainly of n-type. SPUD were manufactured on stably working microelectronic enterprises using the technologies of manufacturing of integrated microelectronics, which have been developed by decades [2].

Silicon planar uncooled detectors have received maximum growth under the development and creation of track systems for supercollider experiments in high-energy physics [3 - 7]. Detecting systems based on SPUD have good energy resolution at room temperature, high spatial and time resolution, high efficiency of low-energy X-ray radiation registering.

Single-channel SPUDs were designed as test structures for measuring individual electro-physical characteristics of detectors during designing of multi-channel Si detectors [8]. Single-channel SPUDs can be also used independently in nuclear physics research and can be applied in medical diagnostics, nondestructive testing systems and environmental control systems.

It was shown in [1], that it is possible to create a sealed detector module using a single-channel SPUD for simultaneous registering of X-ray radiation and low-energy electrons produced in metallic gadolinium during capture of thermal neutrons.

In this paper we present a block diagram of a two-channel spectrometric detection system for registering thermal neutrons. In the first channel of the spectrometric system, the detection module contains only a silicon detector with dimensions of the active region of 5×5 mm and a thickness of 0.3 mm. In the second channel, the detection module contains a silicon detector with a metal Gd converter. The paper also describes a method for determining the thermal neutron flux density with the possibility of excluding background radiation.

1. ENERGY RESOLUTION OF UNCOOLED SILICON PLANAR DETECTORS

Fig. 1 shows a microphotograph of a single-channel SPUD.

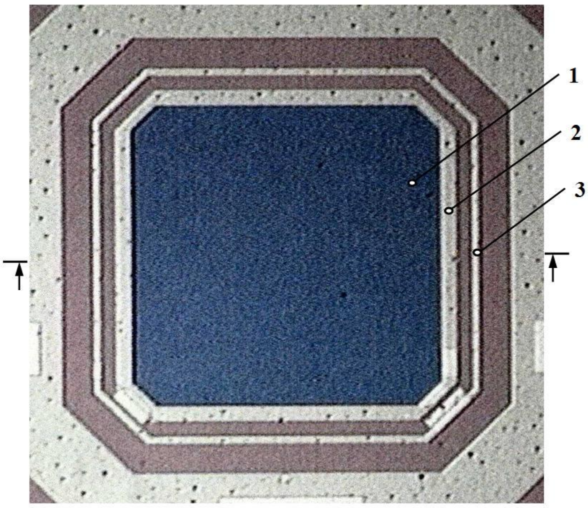

Fig. 1. A microphotograph of a single-channel silicon planar uncooled detector (SPUD): 1 – working area of the detector; 2 – collection ring of the working area; 3 – guard P^+ ring

The single-channel SPUD, shown in the figure, has a complex construction. The main active additional element of the single channel CPDN is the guard P^+ ring (3), made as an independent ring detector. P^+ ring improves the characteristics of the detector, including the energy resolution, because it shorts the edge currents of the detector. The surface of the working area of the detector is not metallized. This reduces the thickness of the dead layer of the working area of the SPUD. A thin metallized ring (2) is formed at the perimeter of the detector working area in order to collect the charge from the working region of the SPUD.

The P$^+$ ring also limits the working area of the detector. This is important for determining the particle flux density and will be discussed in Section 4 of the paper.

Fig. 2 shows the results of measurements of the gamma-ray spectrum of an isotope source of ^{241}Am with a single-channel uncooled Si detector with a thickness of 0.3 mm and working area dimensions of 2×2 mm.

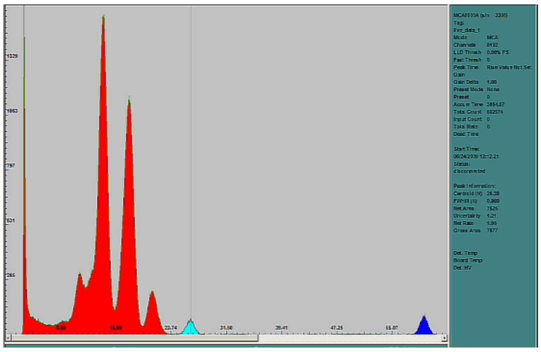

Fig. 2. Results of measurements of the gamma-ray spectrum of an isotope source ^{241}Am by an uncooled silicon detector. The blue peak corresponds to the emission line with an energy of 26.35 keV of the ^{241}Am source

X-ray quanta were detected by a sealed detection module with an aluminum foil inlet of 7 µm thick. The energy resolution is 0.9 keV for the radiation line with an energy of 26.35 keV (blue peak) of the ^{241}Am source. The measurements were carried out using a preamplifier with resistive feedback made at NSC KIPT.

The characteristic X-ray radiation (CXR), excited in various materials (Figs. 3 and 4), was also used for experimental studies of the SPUD energy resolution.

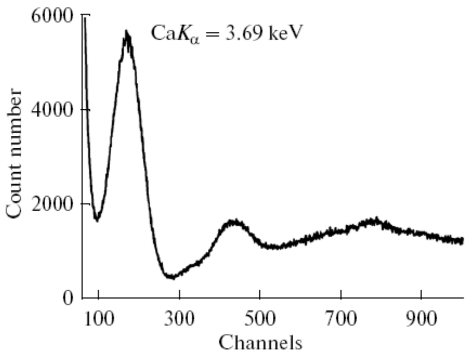

Fig. 3. Results of the calcium CXR line measurements

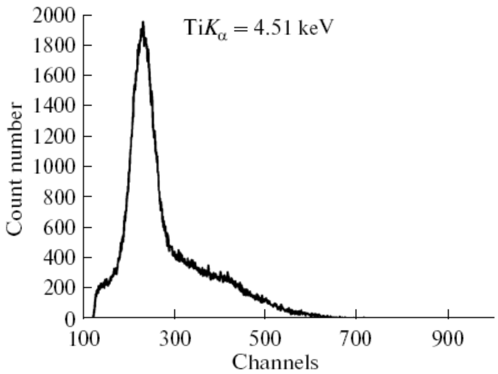

Fig. 4. Results of the titanium CXR line measurements

Ca and Ti CXR were excited by an X-ray tube with a bremsstrahlung peak of 10 keV. On the Figs. 3 and 4 one can see that the CXR of Ca and Ti lines with an energy of 3.69 keV and 4.51 keV are confidently recorded. The low thickness of the dead layer of the SPUD (about 1 µm) makes it possible to record and measure the energy of low-energy particles, what is very important in developing a spectrometric detection system for recording thermal neutrons using a metallic gadolinium converter.

2. ELECTRONICS OF THE TWO-CHANNELS SPECTROMETRIC SYSTEM

The block diagram of the two-channels spectrometric detection system consists of two detecting modules, two charge sensitive amplifiers (CSA), two spectrometric amplifiers, two USB power supplies and two spectrometric analogue-digital converters (ADC) connected to a computer or laptop. A block diagram of a two-channels spectrometric detection system is shown in Fig. 5.

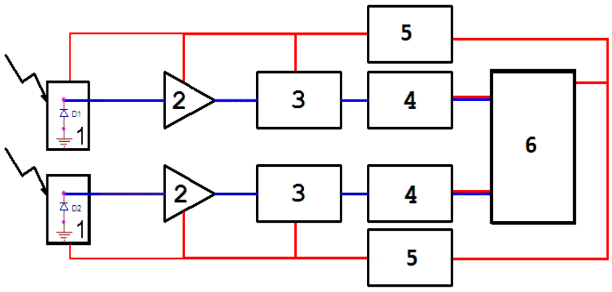

Fig. 5. Block diagram of a two-channel spectrometric detection system: 1 – detection modules; 2 – charge sensitive amplifiers; 3 – spectrometric amplifiers; 4 – spectrometric ADC; 5 – DC/DC converters; 6 – computer or laptop

The charge sensitive amplifier is a direct current amplifier capable of working with planar detectors with a capacitance of up to 10 pF and an input current of up to 10 nA (with a 250 MΩ feedback resistor). The CSA is designed as a direct current amplifier with an open-loop gain more then 80 dB and a single-gain frequency more then 200 MHz.

A field effect transistor with a leakage current of no more than 5 pA (at a temperature of 25°C) and a high slope of ≈22 mA/V (also at a temperature of 25°C) is applied at the input of the CSA. These characteristics provide a low noise (0.8 nV/√Hz) at the frequency of 100 kHz, which is applied to the input of the zero-capacitance input of CSA. Typical transmission factor of the amplifier is not less than 1 V/pC. A typical rise time of the signal of 10…90% at the output of the CSA does not exceed 50 ns at 2 pF of the detector capacity.

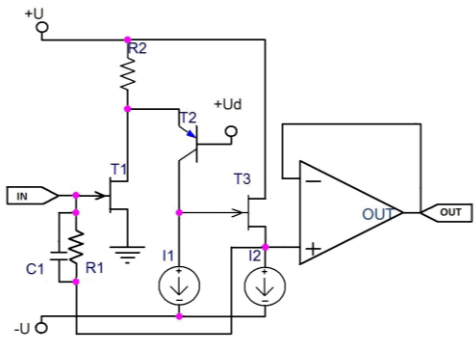

Fig. 6. The simplified scheme of the charge-sensitive amplifier

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The dynamic range of signals at the output is not less than 2 V. Fig. 6 shows a simplified scheme of a charge-sensitive amplifier.

Transistor T1 is a low-noise JFET with a small capacitance Cgs <8 pF and a low gate current Ig <1 pA, which provides a high input impedance of the circuit. The signal from the detector is fed directly to the gate of the transistor T1, which ensures minimal distortion of the signal. Resistor R2 sets the drain current T1. The voltage on the drain T1 is set by the voltage on the base of the transistor T2. The transistor T2 is connected with the transistor T1 to the drain-emitter cascade to extinguish the Miller effect at the input of the circuit, which significantly reduces the effective input capacitance of the CSA and its noise, and also significantly improves the frequency transfer characteristic. The collector T2 is loaded onto the current generator I1, which provides a high gain with open feedback. Typical operating current of transistor T2 is 0.1 mA, which is enough to exclude the reduction of transistor frequency response. However, this current is a low enough to not cause an increase in the successive noise brought to the input. Transistor T3 acts as a buffer with a high input resistance between the collector T2 and feedback. The feedback circuit consists of a high-resistance resistor R1 and a capacitor C1. Its typical configuration is 1 GΩ resistor R1 and 1 pF capacitor C1, which will give an exponential decay constant of the signal at the circuit output of 1 µs. The output of the CSA is further buffered by an operational amplifier.

Fig. 7 shows the oscillogram of the response of the CSA to the charge coming from the detector connected to the input of the amplifier.

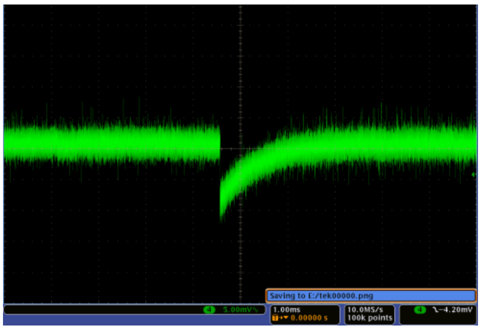

Fig. 7. Typical oscillogram of the pulse at the output of the DCS. The rise time of the signal is 50 ns, the decay time is 1 µs

This is an exponentially damped pulse, the leading front of which determines the charge collection time in the detector and the rise time of the signal in the CSA. The typical value of the rise time for the circuit shown above (see Fig. 6) is 50 ns at a detector capacitance of 2 pF. The decay time of the signal depends on the feedback constant of the charge-sensitive amplifier and its typical value is 1 µs. This decay time specifies the maximum load (pulses/s) from the detector, since in the case of superimposing signals, distortions of the radiation spectrum will appear.

Fig. 8 shows the frequency response of the CSA obtained using the PSpice A/D analysis package.

The frequency of the unit gain is not less than 200 MHz, and the decrease in the frequency response of 6 dB/octave is observed up to 20 dB, which at a capacitance of the input transistor of 7…8 pF allows to work stably with detectors that have a capacity of 2 at 1 pF capacitor in the feedback circuit.

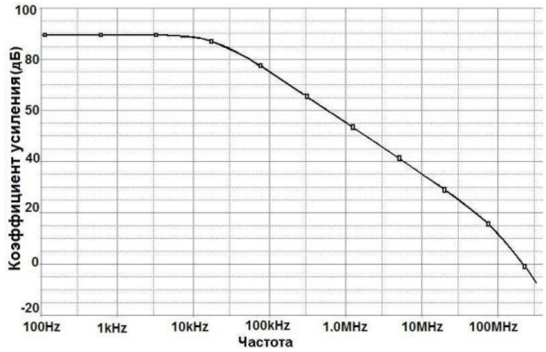

Fig. 8. Dependence of the gain modulus of the CSA with the open feedback on the frequency

Fig. 9 shows the noise of the CSA, brought to an equivalent input capacitance of the detector of 2 pF, versus frequency.

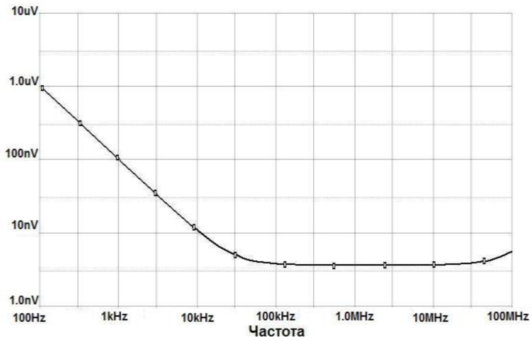

Fig. 9. Frequency characteristic of the noise figure of the CSA, brought to the input capacitance of the detector

Minimal noise is achieved in the frequency band from 100 kHz to 10 MHz, which allows to operate with relatively short generated output pulses with a peak time of the signal from 0.5 to 2 µs. This range is a typical CR-RC time of the signal for the uncooled silicon detectors at room temperature.

Pulses from the charge-sensitive amplifier must be filtered to achieve the maximum signal-to-noise ratio. A frequency band in which a useful signal has the highest energy is released during filtering and those frequencies where noise dominates are suppressed. A semi-gaussian CR-$(RC)^n$ filter is an optimal filter for semiconductor detectors, which makes it convenient to change the filter constants by switching capacitors in the circuit. The filter has a noise excess ratio K_{pn} = 1.16 for fourfold integration.

Fig. 10 shows a simplified schematic diagram of the shaping amplifier for the case of four integrating filters CR-$(RC)^4$.

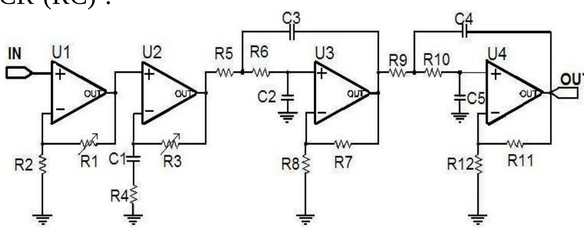

Fig. 10. Simplified circuit diagram of amplifier shaper CR-$(RC)^4$

The input section on the operational amplifier U1 serves as a buffer, which provides a high input impedance at the input and preliminary amplification of a weak signal from the high-frequency amplifier to the required value. The circuit in U2 allows make zero-pole compensation in an exponentially damped signal from the CSA, which is necessary to stabilize the baseline at high pulse counts per second from the detector. The signal is integrated in sections U3 and U4, which are performed as low-frequency filters according to the Sallen-Key scheme.

Fig. 11 shows the oscillogram of the generated pulse at the output of the shaper amplifier with the formation time t_{pk} = 2 μs.

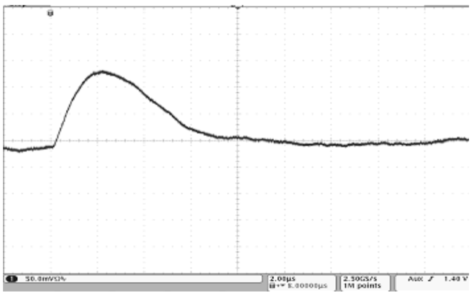

Fig. 11. Semi-gaussian pulse at the output of the shaper amplifier

The total duration of the generated pulse is about $3 \cdot t_{pk}$. For optimal filtering of the signals from planar detectors at room temperatures, it has been experimentally established that peak being formed to 1.5 μs gives the best result, since the current of the uncooled detector gives an additional low-frequency noise, reducing the signal-to-noise ratio for pulses with a long front.

The computer's USB interface voltage (+5V) is used as the primary power source for the convenience of the future device. USB interface is widely used and gives the possibility of power consumption up to 3.5 watts. A DC/DC converter with the following characteristics (Table) was used in order to realize all necessary supply voltages used in the spectrometric device.

Characteristics of DC/DC converter

Input characteristics	
Voltage range	± 10 %
Input voltage	5 V
Input current without load	30 mA
Input current at full load	300 mA
Output characteristics	
Output Voltage	± 12 V
Output current at full load	± 50 mA
Voltage accuracy	± 3%
Short circuit protection	Yes
Pulsation and noise (at 20 MHz bandwidth)	100 mV
Temperature coefficient	± 0.02%/°C

Fig. 12 shows a block diagram of a DC/DC converter.

It includes an input filter with smoothing elements C1 and C2, a DC/DC converter with a dual output. Output voltage converter are fed into the amplifier circuits through the appropriate filters.

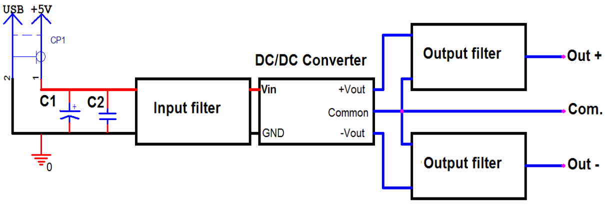

Fig. 12. Block diagram of DC/DC converter

The power of the two-channel spectrometric module is provided from the USB port, the power consumption is not more than 2 W.

3. METHOD OF MEASUREMENT OF THE THERMAL NEUTRONS FLUX DENSITY (FLUENCE)

The method for measuring the thermal neutron flux density is based on the detection of low-energy conversion electrons by uncooled Si detectors formed in metallic gadolinium during neutron capture. Therefore, to measure the neutron flux density by a spectrometric system based on uncooled detectors, it is necessary to provide sufficient energy and spatial resolution, as well as the stability of the spectrometric system. First of all, the design of the applied SPUD contributes to the achievement of these goals.

Fig. 13 shows a simplified cross-section of a single-channel planar silicon detector with a P^+ guard ring.

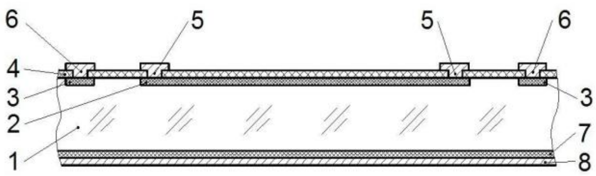

Fig. 13. Simplified cross-section of a single-channel planar silicon detector with a P^+-guard ring: 1 – high-resistance n-type silicon with a thickness of 300 μm; 2 – implantation of the p/n junction of the detector active region; 3 – p/n junction of the P^+-guard ring; 4 – oxide layer of SiO_2; 5 – Al ring for charge collection from the active area; 6 – Al ring of the P^+-guard ring; 7 – n^+-implantation of the back side of the detector; 8 – Al of the back side of the detector

P^+-guard ring 3 in addition to improving the energy resolution of the detector also improves the spatial resolution of the detector. P^+-guard ring very precisely limits the working area of the detector. The edge of the active region of the detector is located in the middle of the gap between the edge of implantation of the p/n junction of the active region of the detector and the edge of implantation of the p/n junction of the P^+-guard ring. The gap between the edge of implantation of the p/n junction of the active region of the detector and the edge of implantation of the p/n junction of the P^+-guard ring is equal to 100 μm.

In Fig. 14 a full description of the cross section of the edge of a single-channel planar silicon detector is presented.

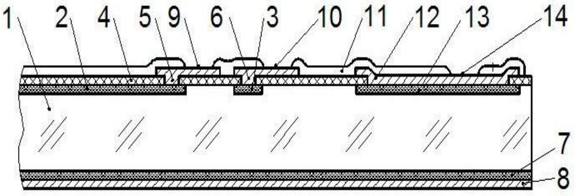

Fig. 14. The cross-section of the edge of a single-channel planar silicon detector: 1 – 8 is the same as in Figs. 13; 9 and 10 contact aluminum sites to p/n junctions of the active region of the detector and P^+ of the guard ring; 11 – passivation (protective) layer of SiO_2 oxide covering the entire surface of the detector with the exception of the pads; 12 – Al ring to the ohmic conductive implantation (13) of the n^+ ring; 14 – Al pad of n^+ protective ring

A protective ohmic current-carrying n^+-ring reduces the bias voltage to the edge of the detector for long-term stabilization of the detector characteristics.

Fig. 15 shows the results of long-term stability testing of the model of a two-channel spectrometric detection system for detecting thermal neutrons based on silicon planar uncooled detectors and a metallic gadolinium converter.

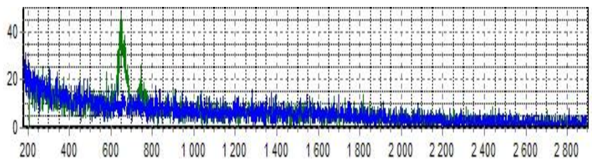

Fig. 15. The results of the long-term stability testing of the model of a two-channel spectrometric detection system for detecting thermal neutrons based on silicon planar uncooled detectors and a metallic gadolinium converter. Axis X is ADC channels, axis Y is the number of events recorded within 15 days. The blue histogram corresponds to the detector without Gd, green – for the detector with Gd

The model of the two-channel spectrometric detection system was tested continuously for 15 days to determine the long-term stability and the intensity of the noise events. As can be seen from the figure, in the 500…2500 channel range, one or less of one noise event in the channel observes (per day). Blue (detector without Gd) and green (detector with Gd) lines coincide with the exception of the range from 600 to 800 channels. In this range of channels on the green line, two CXR gadolinium peaks initiated by cosmic radiation are observed.

Fig. 16 shows the spectral distribution of the radiation of a ^{239}Pu-Be (α, n) neutron source, with a paraffin moderator of 4 cm thickness, measured using a two-channel spectrometric system model.

The method for determining the neutron flux density consists of analyzing data on both channels of the spectrometric system and separating the signal from the conversion electrons. In the range of the expected signal from conversion electrons from 60 keV and higher [1, 9], it is possible to observe deviations in the distribution of data along the detector channel without gadolinium with respect to the channel with the gadolinium converter. The determination of the thermal neutron flux density depends on the number of registered conversion electrons through the conversion electron registration probability coefficient.

From the Fig. 16, one can see that the peaks of conversion electrons 1 and 2 with energies of 71 and 78 keV can be recognized well. The maximum (3) with an energy of 59.5 keV is the CRI line of americium, which is emitted by a neutron source. The maxima 4 and 5 are the gadolinium CXR lines.

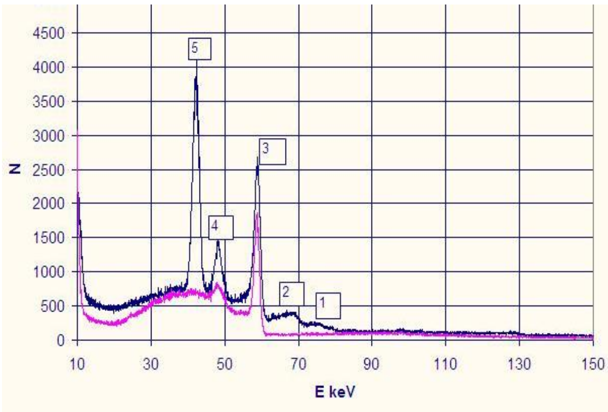

Fig. 16. Spectral distributions of the ^{239}Pu-Be (α, n) radiation of a neutron source, measured using a two-channel spectrometric system model with a paraffin moderator of 4 cm thickness: the lower curve is the spectral distribution measured by a spectrometric channel with a detector without a converter. The upper curve is the spectral distribution measured by the spectrometric channel with the Gd converter. Measurement time T1 is 82591 seconds

Since the model of the two-channel spectrometric system is made using the SPUD with the dimensions of the working areas 5×5 mm (i.e., the working area is 0.25 cm^2), the thermal neutron flux density W_n is determined from the ratio:

$$W_n = \sum e^- \times K_n/0.25 \times \Delta T,\ cm^{-2} \cdot c^{-1},$$

where W_n is the thermal neutron flux density; Σe is the sum of conversion electrons measured in a certain energy interval for a certain time interval by means of a two-channel spectrometric system model; K_n is the coefficient of conformity of the sum of the conversion electrons measured in a certain energy interval over a certain time interval with the number of thermal neutrons measured over the same period of time by the calibration device.

In order to determine the conformity coefficient, the conversion electron energy range 60…80 keV was used. The measurement time T1 is 82591 seconds for the spectrum shown in Fig. 16. For calibration, when determining the conformity factor, a standard, certified PM-21P device was used. The value of the K_n coefficient from the obtained data is 104.2.

Fig. 17 shows the repeated measurement of the spectral distribution of the radiation of the ^{239}Pu-Be source with a paraffin moderator of 4 cm thickness, the measurement time T2 is 129826 seconds.

The value of the conformity coefficient Kn, determined from the data of Fig. 17 is 104.4. A good repeatability of the conformity coefficient K_n indicates a high accuracy of the method for measuring the thermal neutron flux density.

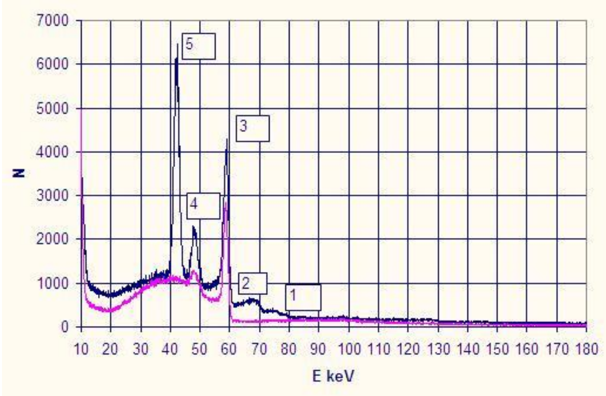

Fig. 17. Results of the repeated measurement of the spectral distribution of the ^{239}Pu-Be (α, n) radiation of a neutron source by the model of a two-channel spectrometric system with a paraffin moderator thickness of 4 cm and a measurement time T2 is 129826 seconds

CONCLUSIONS

A block diagram was developed and a working model of small-sized two-channel spectrometric detection system for recording thermal neutrons was produced. The spectrometric system is created on the basis of silicon planar uncooled detectors and a metallic gadolinium converter.

A method for measuring the flux density (fluence) of thermal neutrons for use in nuclear physics and nuclear medicine has been developed. The coefficient of conformity K_n of the sum of conversion electrons measured in a definite energy interval for a certain time interval with the number of thermal neutrons measured over the same time interval by a calibration device was determined experimentally. The value of the coefficient of conformity K_n, determined from the experimental data of Figs. 16 and 17 is 104.4.

It is shown that a two-detector spectrometric system based on planar Si detectors and Gd converter allows thermal neutrons to be registered by measuring the output of conversion electrons with the possibility of accounting of background radiation. The fast neutron source ^{239}Pu-Be (α, n) and the paraffin moderator were used in the experiments.

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МЕТОДИКА РЕГИСТРАЦИИ ТЕПЛОВЫХ НЕЙТРОНОВ ДВУХКАНАЛЬНОЙ СПЕКТРОМЕТРИЧЕСКОЙ СИСТЕМОЙ НА ОСНОВЕ НЕОХЛАЖДАЕМЫХ Si-ДЕТЕКТОРОВ И ГАДОЛИНИЕВОГО КОНВЕРТОРА

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Разработана блок-схема и выполнено макетирование малогабаритной двухканальной спектрометрической детектирующей системы для регистрации тепловых нейтронов. Спектрометрическая система создается на основе кремниевых планарных неохлаждаемых детекторов и конвертора из металлического гадолиния. Разработана методика измерения плотности потока (флюэнса) тепловых нейтронов для применения в ядерной физике и ядерной медицине. Двухдетекторная спектрометрическая система на основе планарных Si-детекторов и Gd-конвертора позволяет выполнять регистрацию тепловых нейтронов по выходу конверсионных электронов с возможностью учета фонового излучения. В экспериментах использовался источник быстрых нейтронов ^{239}Pu-Be (α, n) и парафиновый замедлитель.

МЕТОДИКА РЕЄСТРАЦІЇ ТЕПЛОВИХ НЕЙТРОНІВ ДВОКАНАЛЬНОЮ СПЕКТРОМЕТРИЧНОЮ СИСТЕМОЮ НА ОСНОВІ НЕОХОЛОДЖУВАНИХ Si-ДЕТЕКТОРІВ І ГАДОЛІНІЄВОГО КОНВЕРТОРА

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Розроблено блок-схему і виконано макетування малогабаритної двоканальної спектрометричної детектуючої системи для реєстрації теплових нейтронів. Спектрометрична система створюється на основі кремнієвих планарних неохолоджуваних детекторів і конвертора з металевого гадолінію. Розроблено методику вимірювання щільності потоку (флюенсу) теплових нейтронів для застосування в ядерній фізиці та ядерній медицині. Дводетекторна спектрометрична система на основі планарних Si-детекторів і Gd-конвертора дозволяє виконувати реєстрацію теплових нейтронів по виходу конверсійних електронів з можливістю обліку фонового випромінювання. В експериментах використовувались джерело швидких нейтронів ^{239}Pu-Be (α, n) і парафіновий сповільнювач.