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THE INVESTIGATION OF MECHANISMS OF FAST NEUTRON REGISTRATION IN OXIDE SCINTILLATORS

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The contributions of gamma rays from the inelastic scattering reaction and the resonant reaction in the process of slowing down fast neutrons inside the oxide detector volume are investigated. For this the countable efficiency of the $ZnWO_4$, $CdWO_4$, $Bi_4Ge_3O_{12}$ oxide scintillators in terms of pulses/neutron during the registration of the fast neutrons from a ^{239}Pu-Be source was measured. It is assumed that the response of detectors during neutron moderation in oxide scintillators with an effective thickness of about 40—50 mm is formed by instantaneous gamma rays from inelastic, resonant inelastic scattering reactions, as well as delayed gamma rays from the capture reaction of resonance neutrons. The parameters of the nuclei, which determine the detector response — the density of the nuclear levels of the compound nuclei being formed, the widths of the resonance regions, the lifetimes of the excited nucleus state were considered. It was found that the registration of a cascade of gamma rays from the discharge of excited levels leads to a significant increase in the countable efficiency of the detector and, as a consequence, an increase in the sensitivity of the detector to fast neutrons. The measured response in terms of pulses/neutron for the ZWO detector — 64, for CWO — 36, for BGO — 2.5. The response of the detectors was recorded by the broadband tract with a time feedback of $\tau\sim$ 0.7 ns. The measured values of the efficiency are explained by the fact that, in our case, the reaction of inelastic scattering is the starting process, which starts the process of discharging nuclear long-lived ($\sim$ 1–1000 ns) states excited in both inelastic scattering and in resonance capture reaction. The registration of the gamma-quanta from discharge leads to an increase the countable efficiency of the detector. The observed increase of the countable efficiency of the secondary gamma quanta is realized when neutrons are moderated inside the oxide detectors with a thickness of 40—50 mm or more. The measurement error of the registration efficiency was about 7%.

KEY WORDS: detector, fast neutrons, excited states, countable efficiency, density of nuclear levels.

The creation of highly sensitive detectors for neutron and gamma-neutron radiation monitoring systems is an important task. The study of the response of single-crystal detectors under irradiation with fast neutrons is being done to develop efficient neutron and gamma-neutron detectors to control the unauthorized movement of fissile and radioactive materials. The goal of this work is to determine the countable efficiency of ZWO ($ZnWO_4$), CWO ($CdWO_4$), BGO ($Bi_4Ge_3O_{12}$) oxide single-crystal scintillators used in the registration of fast neutrons from a ^{239}Pu-Be source. In this work, also the contributions of the mechanisms of neutron energy conversion to secondary gamma quanta during moderation in the detector material also were studied. Earlier, in [1, 2], it was shown that the mechanism of inelastic scattering $(n, n'\gamma)_{in}$ in the energy range of 0.1–10 MeV can be used to register fast neutrons of the ^{239}Pu-Be source with heavy oxide scintillators [3–5].

In this paper, it is assumed that the response from detectors during neutron moderation in oxide scintillators is formed by instant gamma quanta of inelastic, resonance inelastic scattering, as well as delayed gamma quanta of radiation capture in the resonance region emitted by excited states of both compound nuclei and nuclei – products reactions. When fast neutrons are moderated in detector volume with a thickness of 4–5 cm and a resonance region of energies is $E \sim 0.1 - 100$ keV, in addition to the inelastic scattering reaction $(n, n'\gamma)_{in}$, inelastic resonance scattering $(n, n'\gamma)_{in\_res}$ is possible with the emission of instantaneous gamma quanta, since the lifetime of a compound nucleus is very short. In this reaction $(n,n'\gamma)_{in}$, $n+A \to (A+1)^* \to A+n'+\gamma_{prt}$, the neutron emitted from the nucleus, having a significantly lower energy, is more likely to be re-captured by the nucleus in the radiation capture reaction in the resonance region $(n,\gamma)_{rad\_cap\_res}$ and form a new compound-core: $n+A \to (A+1)^* \to (A+1)+\gamma_{del}$, in which long-lived states are excited with lifetimes from some nanoseconds to some microseconds, which genetically related to quanta of the primary reaction of inelastic $(n,n'\gamma)_{in}$ scattering [6, 7]. Thus, the inelastic scattering reaction $(n,n'\gamma)_{in}$ is the "trigger", which starts the cascade process of creation and discharge of excited states in the nuclei of the crystals under study. It is the inelastic $(n,n'\gamma)_{in\_res}$ channel of resonance scattering and radiative capture $(n,\gamma)_{rad\_cap\_res}$ that serves as an effective source of additional neutrons and gamma quanta capable of generating gamma quantum cascades. If the lifetimes of the excited states are in the range of some nanoseconds and above, then registering the detector response using the broadband setup leads to increase the detector countable efficiency and, consequently, to increase the sensitivity to neutron and gamma radiation.

RESEARCH METHODS

To estimate the registration efficiency, we used the parameter "countable" efficiency or $pulses * s^{-1} * cm^{-2}/neutron * s^{-1} * cm^{-2}$ – the ratio of the detector count rate from $S_{win.det} = 1\ cm^{-2}$ to the particle flux density on the detector. In fact, if the detector had a window area of 1 cm^{-2}, then the number of pulses per one input particle was measured. Note that the energy efficiency of the detector cannot exceed 1, while the countable efficiency of the detector, in which multiple processes are possible, accompanied by the creation of a cascade of low-energy particles, may exceed 1.

A fast neutron with an energy of $E_n < 10$ MeV in the process of scattering and moderation in the detector material with linear dimensions of $\sim 3-5$ cm passes the energy range from 10 MeV to a few keV or less. This makes it possible to use, for the purposes of detection, processes that have, firstly, high cross sections for neutron interaction and, secondly, effectively produce secondary particles, for example, gamma rays, recoil protons. The processes generated a long-lived states exited with lifetimes ranging from some nanoseconds to some microseconds are due to the inelastic scattering $(n,n'\gamma)_{in}$, radiation capture in the resonance region $(n,\gamma)_{rad\_cap\_res}$ (Fig. 1).

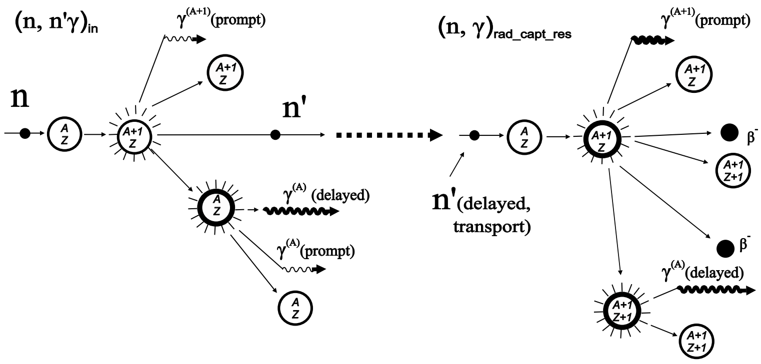

Fig. 1. The processes of inelastic scattering $(n,n'\gamma)_{in}$, radiation capture in the resonance region $(n,\gamma)_{rad\_capt\_res}$, in which instantaneous and delayed secondary gamma quanta produce in the range of 1 ns – 1 μs or more.

For the nuclei of the natural isotopic mixture the cross sections for inelastic scattering $(n,n'\gamma)_{in}$, inelastic resonance scattering $(n,\gamma)_{in\_res}$, radiation capture $(n,\gamma)_{rad\_cap\_res}$ with $E = 14$ MeV, radiation capture in the resonance region $(n,\gamma)_{rad\_cap\_res}$, radiation capture in the thermal region $(n,\gamma)_{rad\_cap}$ (see Table 1) were used from nuclear data bases [8, 9].

Measurement of the countable efficiency of the single-crystal ZWO, CWO, BGO detectors under irradiation of ^{239}Pu-Be source fast neutrons was carried out in spherical geometry [10], the photomultiplier was Hamamatsu R1307, the distance to the source detector was 1000 mm. ^{239}Pu-Be neutron source with a neutron flux of $0.95 \cdot 10^5$ neutron$*s^{-1}$ was used. The source was placed inside a lead ball Ø100 mm with a well Ø20 mm. The source size is Ø20x30 mm, weight is 52 g. The lead ball, besides the main task of reducing the influence of the accumulation factor in the material of the ball, simultaneously attenuates the accompanying gamma radiation from the ^{239}Pu-Be source. In the neutron source there is a concomitant high-energy gamma radiation from the reactions: ^{4}He+^{9}Be $\to$ ^{13}C* $\to$ ^{12}C*+n$\to$^{12}C+γ+n, $E_\gamma = 4.43$ MeV, ^{13}C* $\to$ ^{13}C+γ, $E_\gamma = 3.68$ MeV. In connection with the incomplete suppression of the accompanying high-energy gamma-quanta from the ^{239}Pu-Be source, an correction was add to the efficiency of detecting fast neutrons by registering gamma-quanta with energy $E_\gamma = 4.43$ MeV, which was $\simeq 0.08$ for the ZWO oxide scintillator. It is consist of the γ/n ratio for the ^{239}Pu-Be source, equal to 0.71 [11], the absorption of gamma rays with an energy of 4.43 MeV in d=40 mm of lead, which was 0.15, the absorption efficiency of gamma quanta with an energy of 4.43 MeV in ZWO Ø50 mm was $\simeq$ 0.80. The correction for the absorption of fast neutrons in a protective lead ball due to the radiative capture reaction (n,γ) was determined experimentally using a ^{6}LiI(Eu) detector and amounted to 2.5%. The size of the scintillator ^{6}LiI(Eu) is Ø15x10 mm, the enrichment in ^{6}Li is 96%. The thermal peak (α+t) for ^{6}LiI(Eu) had a gamma equivalent of 3.98 MeV, fast neutrons were recorded in the energy range 3.98 MeV ÷ 10 MeV. The correction for gamma rays with energy E = 4.43 MeV was taken into account. The contribution of scattered fast neutrons from the walls of the room did not exceed 3%. The correction is determined using a ^{6}LiI(Eu) detector by measuring the deviation from the inverse square law when registering fast neutrons. The contribution of scattered gamma radiation in the source-detector distance range R = 1÷2 m did not exceed $\sim$ 1%. The correction is determined by measuring the deviation from the inverse square law when registering ^{137}Cs quanta. An additional 5 mm thick lead shield served to protect the detectors from background gamma radiation. The background attenuation coefficient in the range of 10 keV-150 keV is $\simeq$ 3.

Table 1

Cross sections of inelastic scattering reactions $(n,n'\gamma)_{in}$, inelastic resonance scattering $(n,n'\gamma)_{in\_res}$, radiation capture $(n,\gamma)_{rad\_cap\_in}$, radiation capture in the resonance region $(n,\gamma)_{rad\_cap\_res}$, radiation capture in thermal region $(n,\gamma)_{rad\_cap}$ for the nuclei of the natural isotopic mixture that made scintillators BGO, CWO, ZWO.

Isotops mixture, nat.	Reactions	σ, barn (E = 0.0253 eV)	σ, barn, (res.) (0.5 eV- 10 MeV)	σ, barn (E = 14 MeV)	$E-$ thresh., keV
$_{48}$Cd	$(n,n'\gamma)_{in}$	-	-	0.4163	247.6
	$(n,\gamma)_{rad\_cap\_in}$	-	-	0.8386 mb	-
	$(n,\gamma)_{rad\_cap\_res}$	-	66.59	-	-
	$(n,\gamma)_{rad\_cap}$	2468	-	-	-
$_{74}$W	$(n,n'\gamma)_{in}$	-	-	0.4281	46.74
	$(n,\gamma)_{rad\_cap\_in}$	-	-	0.7421 mb	-
	$(n,\gamma)_{rad\_cap\_res}$	-	355.1	-	-
	$(n,\gamma)_{rad\_cap}$	18.15	-	-	-
$_{30}$Zn	$(n,n'\gamma)_{in}$	-	-	0.6192	94.72
	$(n,\gamma)_{rad\_cap\_in}$	-	-	0.924 mb	-
	$(n,\gamma)_{rad\_cap\_res}$	-	2.539	-	-
	$(n,\gamma)_{rad\_cap}$	1.062	-	-	-
$_{83}$Bi	$(n,n'\gamma)_{in}$	-	-	0.3611	900.7
	$(n,\gamma)_{rad\_cap\_in}$	-	-	0.756	-
	$(n,\gamma)_{rad\_cap\_res}$	-	0.1715	-	-
	$(n,\gamma)_{rad\_cap}$	0.03421	-	-	-
$_{32}$Ge	$(n,n'\gamma)_{in}$	-	-	0.5655	-
	$(n,n'\gamma)_{in\_res}$	-	3.684	-	-
	$(n,\gamma)_{rad\_cap\_in}$	-	-	-	-
	$(n,\gamma)_{rad\_cap\_res}$	-	5.997	0.5333 mb	-
	$(n,\gamma)_{rad\_cap}$	2.217	-	-	-

The statistical error in measuring the neutron registration efficiency was 7% for detectors with an effective thickness of d $\simeq$ 40 mm. The data accumulation time was 100 minutes for the source irradiation and the same time for background accumulation.

The block diagram of the electronic measuring setup, which includes PMT the Hamamatsu R1307 and a low-noise fast amplifier, is given in [12]. The signals with PMT amplitude from 2 mV (total noise of PMT and electronics was 10 mV) were amplified by a wideband (Δf$\simeq$500 MHz) preamplifier. In this time domain, both instantaneous signals from gamma quanta that occur in inelastic and resonance neutron scattering and capture reactions, and discharge signals from long-lived ($\tau \simeq$ 1–1000 ns and more) nuclear states excited in reactions with neutrons can be present. In Fig. 2 shows the simultaneously registered signals (pulses /1 neutron) under the interaction of fast neutrons with the ZWO detector: the upper figure is from the broadband setup, $\tau \sim 7$ ns, taking into account the PMT, the lower figure is from the narrow-band path, $\tau \sim 1$ μs. Signals at the output of the preamplifier and at the input of the ADC were recorded by counters and observed with an oscilloscope.

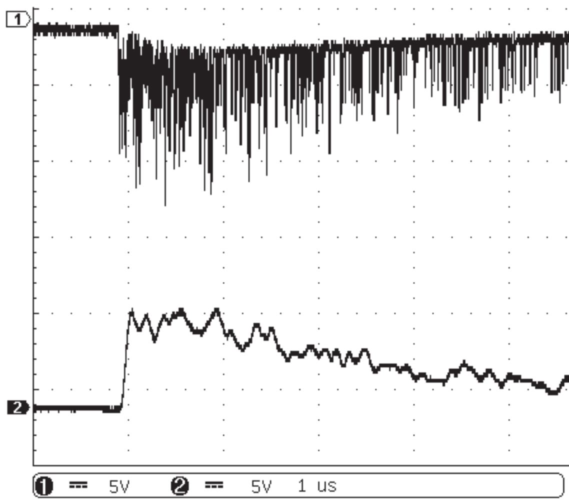

Fig. 2. Simultaneously registered signals forms (pulses / 1 neutron) for the ZWO detector. The upper pattern is from a broadband setup, the lower pattern is from a narrowband setup. X axis — time, 1 division = 1 μs. Y axis — volts. Visualisation — 500 MHz oscilloscope.

In accordance with the thermodynamic model of nuclei reactions [13] the average energy of the final products, temperature of nuclei in the reactions of inelastic scattering $(n, n'\gamma)_{in}$ and resonance radiation capture $(n, \gamma)_{rad\_cap\_res}$ neutrons at nuclei that are part of the oxide scintillators, were estimated Table 2. In calculation we supposed that the ^{239}Pu-Be source has an average neutron energy about 4.5 MeV and a maximum energy about 10 MeV.

In the present work, on the basis of the energy analysis performed, a systematic analysis of the discharge patterns of the states of isotopes excited in reactions with neutrons, which are part of the oxide scintillators available to us, and also formed in compound nuclei was carried out. The suitability of the isotopic composition of the detectors to generate gamma quanta from excited short-lived nuclear states is estimated. The nuclear states excited by fast neutrons with an average energy $E_n \simeq 4.5$ MeV are systematized, their number, the energies of the excited levels are estimated. The density of the levels excited in compound nuclei was estimated based on data from [14]. The results of the analysis for the natural mixture of ^{182}W-^{187}W isotopes that are part of the scintillators are presented in Table 3. A similar analysis also was performed for isotopes — ^{110}Cd – ^{114}Cd, ^{116}Cd, ^{64}Zn, ^{66}Zn, ^{68}Zn, ^{209}Bi.

From the Table 3 it can be seen that the most low-energy gamma-quanta emitted by excited states of the nuclei that make up the scintillators under study have lifetimes in the range of 1-1000 ns, born in inelastic scattering reactions $(n, n'\gamma)_{in}$: $(n+A) \rightarrow (A+1)^* \rightarrow A^*+n'+\gamma_{prt} \rightarrow A+\gamma_{del}+n'+\gamma_{prt}$, (A is the target nuclei, A+1 – compound nuclei). Also a slow neutrons produce gamma-quanta in the reaction of radiation capture in the resonance region $(n, \gamma)_{rad\_cap\_res}$: $(n + A) \rightarrow (A + 1)^* \rightarrow (A + 1) + \gamma_{del}$. It can be assumed that the response of the detector to fast neutrons is determined, firstly, by the registration of instantaneous secondary gamma quanta from inelastic scattering, inelastic resonance scattering and radiation capture in the resonance region. In addition, genetically related cascades of gamma-quanta of discharge of excited states of nuclei in the range of 1–1000 ns from the listed reactions were taken into account. The model response of detectors to fast neutrons was formed on the basis of the cross sections of the main processes, the densities of the levels of the compound nuclei produced during scattering, the width of the resonance region, the number of excited states were taken into account Table 4 [8, 9, 14–16]. The duration of the lifetime of radiation products of short-lived (1–1000 ns) states of the daughter nuclei genetically related to the emitted instantaneous gamma quanta excited in the compound nucleus as in inelastic scattering $(n, n'\gamma)_{in}$ neutrons in the energy range $E_n \sim 0.1\div$ 10 MeV, was also taken into account inelastic resonance scattering $(n, n'\gamma)_{in\_res}$ the energy range $E_n \sim 0.1\div$ 150 keV and radiation capture in the resonance region $(n, \gamma)_{rad\_cap\_res}$. The abundance of the considered isotopes was taken into account.

Table 2

The esimate of the average energy, temperature of the final products in the reactions of neutron inelastic scattering $(n, n'\gamma)_{in}$ for $E_n \simeq 4.5$ MeV, 10 MeV and inelastic radiation capture $(n, \gamma)_{rad\_cap\_res}$ at $E_n \sim 0.15$ MeV on nuclei of oxide scintillators. A – target nuclei, C – compaund nuclei.

$(n, n'\gamma)_{in}$	^{65}Zn	^{182}W	^{65}Zn	^{182}W	$(n, \gamma)_{rad\_cap\_res}$	^{65}Zn	^{182}W
Neutron separation energies, B_n	11.1	6.2	11.1	6.2	Neutron separation energies, B_n	11.1	6.2
T_{n_inp}	4.5	4.5	10	10	T_{n_inp}	0.15	0.15
$U_{ex}, max(C^*)$	15.6	10.7	21.1	16.2	$U_{ex}, max(C^*)$	11.25	6.35
$U_{ex}, max(A^*)$	4.5	4.5	10	10			
$Temperature\,\Theta, (A^*)$	1.5	0.7	2.2	1	$Temperature\,\Theta, (C^*)$	2.4	0.8
$T_{n\_out}, 2\Theta$	3	1.4	4.4	2			
$U_{ex\_remain.}, (A^*)$	1.5	3.2	5.6	8			

Table 3

Parameters of energy states of W isotopes excited by fast neutrons in inelastic scattering $(n, n'\gamma)_{in}$ reactions, radiation capture in the resonance region $(n, \gamma)_{rad\_cap\_res}$.

Reactions	Level energy, keV	Life-time, ns	J^π	Reactions	Level energy, keV	Life-time, ns	J^π
^{182}W(n, n'γ)^{182}W	g.s. 100.1 1289.1	 1.38 1.12	0^+ 2^+ 2^-	^{184}W(n, n'γ)^{184}W	g.s. 111.1 1285	 1.29 8330	0^+ 2^+ 5^-
^{182}W(n, γ)^{183}W	g.s. 308.5 453	 5.3 s 18.5	$1/2^-$ $7/2^-$	^{184}W(n, γ)^{185}W	g.s. 173.7 197.4 243.6	75.1 d 1.5 1.67 min 19.3	$3/2^-$ $7/2^-$ $11/2^+$ $7/2^-$
^{183}W(n, n'γ)^{183}W	g.s. 308.5 453	 5.3 s 18.5	$1/2^-$ $7/2^-$	^{186}W(n, n'γ)^{186}W	g.s. 122.6 1517.2	 1.04 18000	0^+ 2^+ 7^-
^{183}W(n, γ)^{184}W	g.s. 111.1 1285	 1.29 8330	0^+ 2^+ 5^-	^{186}W(n, γ)^{187}W	g.s. 350.4 364.2 410.1	 5 15 1380	$3/2^-$ $7/2^-$ $9/2^-$ $11/2^+$

The registration of gamma-discharge quanta in the region of lifetimes of nuclear states about 1 - 100 ns or more was possible due to the use of the fast preamplifier based on a current – voltage converter with a speed of $\sim$ 500 MHz ($\tau \sim 0.7$ ns). When using the spectrometric tract ($\tau \simeq 1$ μs), the value of the countable efficiency for ZWO and CWO decreases by approximately two orders of magnitude and is 0.6-0.7, that's why significant number of short-lived signals are combined (integrated). In the spectrometric mode, the key role is played by the inelastic scattering cross section, and the secondary reaction products with neutrons are combined into one detector response, which can be called instantaneous. Despite the fact that W and Cd have a large capture cross section in the resonance region, $\sigma_{res}(W) \simeq 355$ b, $\sigma_{res}(Cd) \simeq 67$ b, it does not manifest itself in the spectrometric mode, since the fast detector signals are integrated. Apparently, the secondary products of reactions with neutrons emitted by compound nuclei $C = (A + 1)$ are concentrated in the range from units to several hundred nanoseconds, which confirms experimentally the result of registration. The countable efficiency for BGO during the transition to the spectrometric regime remains almost at the same level, i.e. $\sim$2.5 pulses/neutron. This can be explained by the fact that compound nuclei formed in reactions with BGO nuclei have practically no states with an interval of lifetimes about $1 - 10^3$ ns. In addition, the Bi and Ge nuclei have a small cross section for resonance scattering; therefore, the broadband setup offers no advantages over the narrowband when using a BGO-based detector.

Table 4

Nucleus parameters weighted by the abundance in the natural mixture of isotopes of BGO, CWO, ZWO scintillators: σ_{in}, σ_{res} cross sections, density of levels in the resonance region $\rho(E)$, MeV^{-1}, ΔE of resonance region, keV, lifetime of exited states, gap of exited levels, number of exited levels.

	Nuclei	Z	σ_{in}, barn	σ_r, barn	$\rho(E)$, dens.	ΔE, res.	Exited states τ, ns	Gap of exited levels ΔE_{ex}, keV	Number of excited levels in ΔE_{ex}
ZWO	Zn W	30 74	0.619 0.428	2.539 355.1	230.1 23825	150 5	4000 20	53.9 - 1910 244 - 1200	6 3
CWO	Cd	48	0.416	66.6	14608	9	85	245 - 316	1
BGO	Bi Ge	83 32	0.361 0.565	0.19 5.997	250 538	200 30	59 418	433 - 1500 175 - 5540	2 3

RESULTS

In the present work, experimental values of the countable efficiency for fast neutrons of the ^{239}Pu-Be source for single-crystal BGO detectors – 2.5 pulses/neutron, ZWO – 64 pulses/neutron and CWO – 36 pulses/neutron (Fig. 3, Table 5) are obtained. The data are expressed in units of $(pulses \cdot s^{-1} \cdot cm^{-2}/neutron \cdot s^{-1} \cdot cm^{-2})$, i.e. as a ratio of the countable rate from 1 cm^2 of the detector input window to the neutron flux density on the detector. In fact, this parameter gives the number of pulses from the entire detector, which are generated by one particle falling on the detector. On the Fig. 3, the experimental data are dark columns.

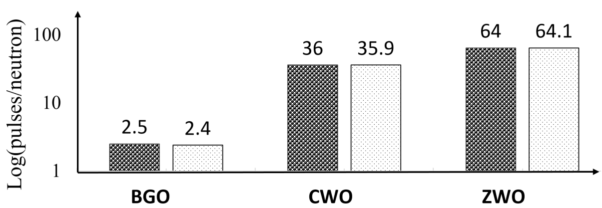

Fig. 3. Response to fast neutrons for BGO — 2.5 pulses/neutron, ZWO — 64 pulses/neutron, CWO — 36 pulses/neutron. Y-axis — ratio of countable rate from 1 cm^2 of the detector input window area to the flux density (pulses/neutron). The experimental data — dark columns, model data — light columns.

Also in this work, a model analysis of the most important, in terms of countable efficiency, characteristics of the nuclear levels of the nuclei that contain the detectors under study is made. The model responce of detectors was defined: R $\Longleftrightarrow \sigma_{in} \otimes \sigma_{res} \otimes \rho(E) \otimes \Delta E_{res} \otimes \Delta E_{ex} \otimes \tau_{ex} \otimes N_{ex}$. The model estimate (light columns, Fig. 3) of the response of the ZWO, CWO, BGO detectors agree quite satisfactorily with the experimental results obtained for the detection countable efficiency of fast neutrons.

Table 5

Experimental countable efficiency and model responce for BGO, CWO and ZWO in $pulses * s^{-1} * cm^{-2}/neutron * s^{-1} * cm^{-2}$ units. Neutron source — ^{239}Pu-Be. Experimental errors $< 7\%$.

Scintillators	Experimental countable efficiency, pulses/neutron	Model countable efficiency, pulses/neutron
BGO	2.5	2.4
CWO	36	35.9
ZWO	64	64.1

CONCLUSIONS

In the present work the countable efficiency of registration of fast neutrons of the ^{239}Pu-Be source for single-crystal detectors BGO, ZWO, CWO were measured. Also the most significant parameters of nuclei that are part of oxide scintillators, such as ZWO, CWO and responsible for improving the efficiency of detecting fast neutrons during their deceleration and entry into the resonance region, namely: inelastic scattering cross section, inelastic scattering cross section and capture in the resonance region, the width of the resonance region, the density of the nuclear levels of compound nuclei, the lifetimes of isomeric states, the energy of the excited levels, the quontity of excited states. The significance of these parameters is experimentally confirmed by an increase in the countable efficiency by about two orders of magnitude for gamma quanta with lifetimes $\tau \sim$ 1–1000 ns for ZWO and CWO single crystal detectors compared to a recording method using a spectrometric amplification mode with $\tau \sim 1\,\mu$s, in which significant suppressions of response pulses from short-lived states. To effectively register the decay quanta of short-lived states, a broadband, fast-acting setup is required.

Thus, the use of heavy oxide scintillators in the countable mode of short impulses of response can significantly improve the registration statistics and the sensitivity of neutron detectors through the use of radiation capture in the resonance region $(n, \gamma)_{rad\_cap\_res}$, in which a chain of secondary gamma-quanta emitted by short-lived nuclear states and which are genetically related to the primary inelastic scattering reaction gamma-quantum $(n, n'\gamma)_{in}$. Note that in this case, the increase in statistics is due to the qualitative effect due to the genetic linkage of the mechanisms, and hence the reaction products. This will make it possible to create neutron and gamma-neutron detectors that are significantly more compact compared to existing ^{3}He-counters for monitoring low-intensity neutron and gamma-neutron fields.

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ИССЛЕДОВАНИЕ МЕХАНИЗМОВ РЕГИСТРАЦИИ БЫСТРЫХ НЕЙТРОНОВ В ОКСИДНЫХ СЦИНТИЛЛЯТОРАХ

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Были изучены вклады гамма-квантов из реакции неупругого рассеяния и реакции резонансного рассеяния в процессе замедления быстрых нейтронов внутри объема оксидного детектора. Для этого измерена счетная эффективность оксидных сцинтилляторов $ZnWO_4$, $CdWO_4$, $Bi_4Ge_3O_{12}$ в терминах "импульсы/нейтрон"при регистрации быстрых нейтронов от источника ^{239}Pu-Be. Предполагается, что отклик детекторов при замедлении нейтронов в оксидных сцинтилляторах с эффективной толщиной около 40–50 мм формируется мгновенными гамма-квантами из реакций неупругого, резонансного неупругого рассеяния, а также задержанными гамма-квантами из реакции захвата замедленных нейтронов в резонансной области. Были рассмотрены параметры ядер, определяющие отклик детектора - плотность ядерных уровней образующихся составных ядер, ширина резонансной области, времена жизни возбужденного ядра состояния. Было установлено, что регистрация каскада гамма-квантов из разрядки возбужденных уровней ведет к значительному повышению эффективности счета детектора и, как следствие, повышению чувствительности детектора к быстрым нейтронам. Измеренный отклик в единицах импульс/нейтрон для детектора ZWO составил 64, для CWO — 36, для BGO — 2,5. Отклик детекторов регистрировался широкополосным трактом с быстродействием $\tau \sim 0{,}7$ нс. Измеренные значения счетной эффективности объясняются тем фактором, что в нашем случае реакция неупругого рассеяния является стартовым процессом, который запускает процесс разрядки ядерных долгоживущих ($\sim 1 \div 1000$ нс) состояний, возбуждаемых как в неупругом рассеянии, так и в резонансном захвате. Регистрация гамма-квантов разрядки приводит к увеличению счетной эффективности детектора. Наблюдаемое увеличение счетной эффективности вторичных гамма-квантов реализуется при замедлении нейтронов в оксидных детекторах толщиной 40–50 мм и более. Погрешность измерений эффективности регистрации нейтронов составляла 7 %.

КЛЮЧЕВЫЕ СЛОВА: детектор, быстрые нейтроны, возбужденные состояния, счетная эффективность, плотность ядерных уровней.

ДОСЛІДЖЕННЯ МЕХАНІЗМІВ РЕЄСТРАЦІЇ ШВИДКИХ НЕЙТРОНІВ В ОКСИДНИХ СЦИНТИЛЯТОРАХ

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Були досліджені внески гамма-квантів із реакції непружного розсіяння і реакції резонансного розсіяння у процесі уповільнення швидких нейтронів всередині об'єма детектора. Для цього виміряна лічильна ефективність оксидних сцинтиляторів $ZnWO_4$, $CdWO_4$, $Bi_4Ge_3O_{12}$ у термінах "імпульси/нейтрон"при реєстрації швидких нейтронів від джерела ^{239}Pu-Be. Зроблено припущення, що відгук детекторів при уповільненні нейтронів у оксидних сцинтиляторах з ефективною товщиною близько 40—50 мм формується миттєвими гамма-квантами із реакції непружного, резонансного непружного розсіяння, а також затриманими гамма-квантами із реакції захвата уповільнених нейтронів у резонансній області. Були розглянуті параметри ядер, які визначають відгук детектора - щільність ядерних рівнів, що утворюються у складених ядрах, ширина резонансної області, час життя збуджених станів ядра. Встановлено, что реєстрація каскаду гамма-квантів із розрядки збуджених станів призводить до значного підвищення ефективності лічення детектора і, як наслідок, до підвищення чутливості детектора до швидких нейтронів. Виміряний відгук у одиницях імпульси/нейтрон для детектора ZWO склав 64, для CWO — 36, для BGO — 2,5. Відгук детекторів реєструвався широкополосним трактом із швидкодією $\tau \sim 0{,}7$ нс. Виміряні величини лічильної ефективності можна пояснити тим фактором, що в нашому випадку реакція непружного розсіяння є стартовим процесом, який ініціює процес розрядки ядерних довгоживучих ($\sim$1÷1000 нс) станів ядер, які збуджуються як у непржному розсіянні, так і у резонансному захваті. Реєстрація гамма-квантів розрядки призводить до зростання лічильної ефективності детектора. Спостережуване зростання лічильної ефективності вторинних гамма-квантів реалізується при уповільненні нейтронів в оксидних детекторах товщиною 40–50 мм і більше. Похибка вимірювань ефективності реєстрації нейтронів складала 7 %.

КЛЮЧОВІ СЛОВА: детектор, швидкі нейтрони, збуджені стани, лічильна ефективність, щільність ядерних рівнів.