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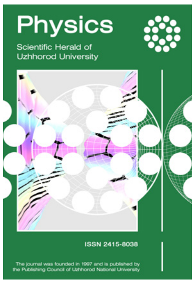

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Enhancement of Gamma-Ray Yield from Fast Neutrons Interaction with Cadmium Isotopes

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Abstract

Purpose. This paper presents the results of investigation of γ-ray yield enhancement from ^{nat}Cd(n, $x\gamma$) reactions obtained in experiments with 14-MeV neutrons in comparison with theoretical spectrum calculated in Empire code.

Methods. The experiment was carried out applying TOF-technique for n-γ discrimination. The MCNP simulation of the experiment was performed and the influence of scattered neutrons background at gamma-ray spectrum shape was estimated.

Results. It was shown that despite TOF-technique thermal neutrons capture by ^{113}Cd isotope gives considerable contribution to gamma-spectrum induced in ^{nat}Cd sample by primary DT-neutrons. The thermal neutron flux was determined to be nearly constant at different locations of experimental hall.

Conclusions. For the correct measurements of the γ-production cross sections for cadmium samples the sufficient separation between primary neutrons and scattered ones must be provided

Keywords: thermal neutrons, DT-neutrons, cadmium, gamma-spectrum, gamma-ray yield

Introduction

The cross sections of gamma-rays production induced by neutron interactions are required for radiation damage and shielding calculations of the fission and fusion reactors. The 14-MeV neutrons are of utmost importance for these tasks because of the big number of open reaction channels at this incident neutrons energy. Almost all of interactions between neutrons and nuclei of interest are accompanied by the prompt gammas emission, and the (n, $x\gamma$) reactions cross sections must be precisely known for the modern and future reactor construction elements undergoing neutron exposure. Despite large number of experiments performed with DT-neutrons they

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are still relevant for fusion reactors design. It is caused by disagreements between nuclear data from different authors [1] or between experimental results and theoretical calculations. In particular, the last ones were obtained in our experiments for Cd element [2], which is commonly used in the reactors industry. The measured gamma-ray spectrum appeared to be enhanced in comparison with theoretical calculations. In this work we present the investigation of this phenomenon.

Data Analysis

Our experiments in gamma-ray spectroscopy were performed with 14-MeV neutrons for different samples, such as ^{nat}Fe, ^{nat}Bi, ^{nat}Cd, ^{nat}Ni, ^{nat}Sn and ^{nat}C [2-5]. All the measurements were carried out using the pulse neutron generator facility PNG-200 under the same geometry (samples had the torus shapes with outer and inner radii of 10÷16.5 cm and 1.5 cm, respectively) and with the same settings: for n-γ discrimination the time-of-flight (TOF) technique was applied with pulse repetition period (PRP) of 140 ns and with γ-detection time window of 20 ns (the detailed description of experiments and DAQ can be found in [4]). A good agreement between experimental results and theoretical calculations performed in Empire code [6] was obtained for all elements except natCd sample, where notable discrepancy in the 5÷10 MeV energy range is observed (Fig. 1). Such enhancement of measured gamma-spectrum from ^{nat}Cd was also observed in works of other authors [7; 8].

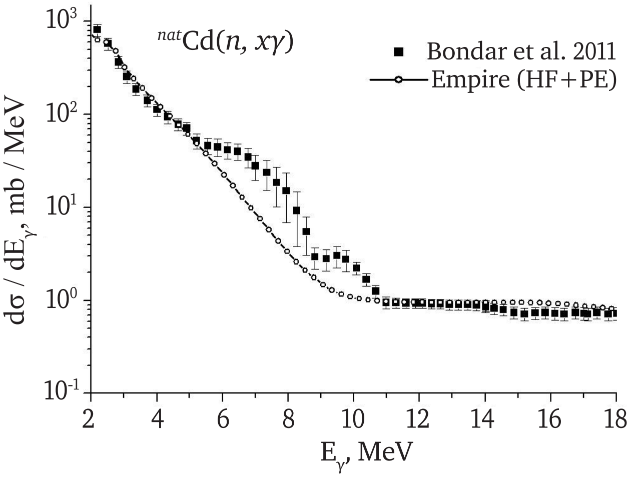

Figure 1. The experimental data and theoretical calculations of gamma-ray spectrum from ^{nat}Cd(n, $x\gamma$) reactions induced by 14-MeV neutrons

The origin of this discrepancy can be caused by the experimental conditions such as presence of thermal neutrons background. The neutron scattering on construction elements and walls of the experimental hall leads to continuous neutron spectrum formation in the experimental hall, as well as the sample itself, and takes much longer than PRP time. Hence, despite TOF technique, the background gammas induced by low-energy neutrons interaction can also be detected in the time window. It is well-known that for ^{nat}Fe, ^{nat}Bi, ^{nat}Ni, ^{nat}Sn and ^{nat}C elements capture cross section even for thermal neutrons does not exceed several barns. But for ^{nat}Cd this value is about 2500 b, and (n, γ) reactions can cause an essential impact on gamma-ray spectrum.

An additional contribution to γ-spectrum is mainly expected to be from the ^{113}Cd(n, γ) ^{114}Cd nuclear reaction. The ^{113}Cd isotope has 12.23% in natural abundance and average cross section of 20 000 b for thermal neutrons capture resulting in formation of compound nucleus ^{114}Cd with excitation energy 9.04 MeV. The de-excitation of this state occurs with high probability by the cascade E2 transitions through the discrete levels 0-558.45 keV-1283.7 keV-1991 keV-2670 keV, accompanied by gamma-rays with the energies 9.04 MeV, 8.48 MeV, 7.76 MeV, 7.05 MeV, and 6.37 MeV (Fig.2).

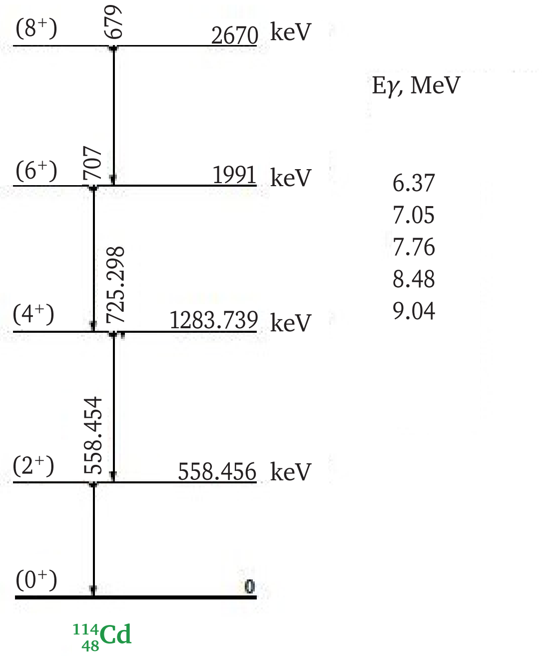

Figure 2. Possible γ-transitions from the ^{113}Cd(n, γ) ^{114}Cd reactions at excitation energy of 9.04 MeV

The energy resolution for these energies in experiment was near 1 MeV, so along with continuum transitions these gamma-rays due to neutron capture could provide smooth enhancement of gamma-spectrum within the energy interval 5÷10 MeV. The continuum transitions from ^{113}Cd(n, γ)^{114}Cd reactions give notable contribution below 7 MeV [9], therefore the observed double-humped spectrum can be formed by the sum of a group of peaks around 7 MeV and the continuous spectrum increasing at lower energies (left part), and discrete gamma-rays with energies from 7.05 to the 9.04 MeV in the right part of the spectrum. All these considerations indicate possible influence of low-energy neutrons. To figure this out, the scattered neutrons fluxes must be determined.

MCNP Simulations

The 14-MeV and thermal neutrons fluxes were estimated by MCNP [10] simulations. The geometry of the experiment is presented in Figure 3. The main components that can effectively moderate neutrons, such as concrete walls, floor, roof and oil filled bucket for high voltage supply were also built for simulations.

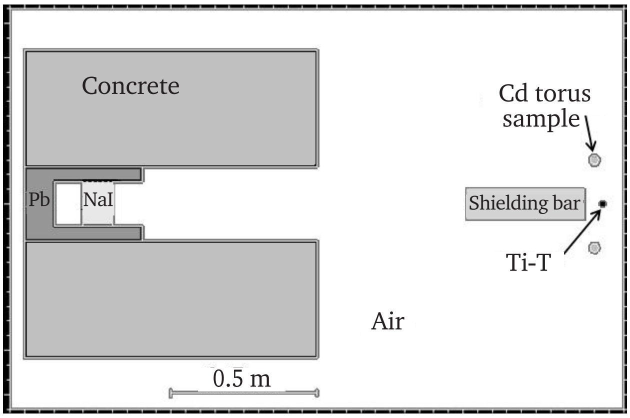

Figure 3. The MCNP geometry of the experiment

The overall time of neutrons moderation to the thermal energies and subsequent diffusion before absorption is several hundreds of microseconds. The PNG-200 generates pulses of DT-neutrons with period of 0.14 μs, so it can be considered as constant neutrons source relative to the scattered neutrons lifetime in experimental hall. In such conditions the flux of thermal neutrons is statistically averaged and nearly constant during the measurements with strong dependence on intensity of DT-neutrons from the Ti-T target. Therefore the continuous and isotropic point-source of 14-MeV neutrons was specified in simulations.

The neutrons fluxes per one DT-neutron from the source were determined at different locations in the experimental hall: near the sample, behind the shielding bar and near the wall, which is at 3.5 m distance from Ti-T target. The results of simulated fluxes are shown in Table 1.

Table 1. Primary 14-MeV and scattered low-energy (0÷0.5 eV) neutron fluxes at different locations

Location	F_{14}, 1/cm²/DT – neutron (14 MeV)	F_{th}, 1/cm²/DT – neutron (0÷0.5 eV)
Near the sample	$2.92 \cdot 10^{-4}$	$9.66 \cdot 10^{-7}$
Behind shielding bar	$9.57 \cdot 10^{-6}$	$9.48 \cdot 10^{-7}$
Near the wall	$7.59 \cdot 10^{-7}$	$9.65 \cdot 10^{-7}$

The simulated neutron spectra near the sample within the 0.1÷15 MeV and 0÷0.5 eV energy ranges are shown in Figure 4 The ratio between 14-MeV (F_{14}) and thermal (from 0 and up to 0.5 eV, F_{th}) neutron fluxes near the sample appeared to be $F_{14}/F_{th}=302.3$.

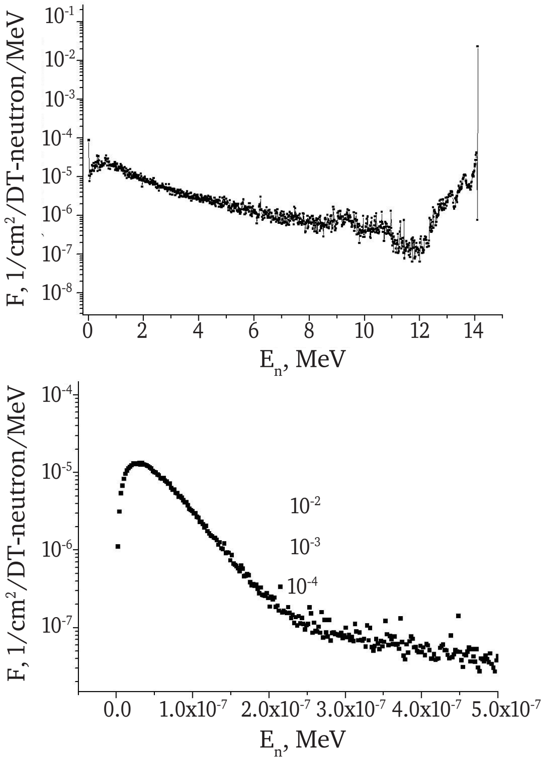

Figure 3. Simulated neutron spectra near the ^{nat}Cd sample

The yield of gamma-rays from (n, xγ) reactions induced by 14-MeV neutrons in the ^{nat}Cd sample equals (1):

$$Y_{14} = N_{14} F_{14} \alpha_n \sigma_{14} \qquad (1)$$

where N_{14} is the number of nuclei undergoing irradiation by 14 MeV neutrons; F_{14} is the 14-MeV neutron fluence; αn – coefficient for 14-MeV neutrons beam attenuation in the sample; σ_{14} – cross section of gamma-production from (n, $x\gamma$) reactions induced by 14-MeV neutrons. In case of thermal neutrons, the high cross section of radiative capture by ^{113}Cd isotope limits the free path of thermal neutron in cadmium by the value of $\lambda_{th}=1/\Sigma_{th}=8.6*10^{-3}$ cm. As a result, all the thermal neutrons are absorbed within a thin ($x<$ 0.1cm) layer of cadmium, and (n, γ) reactions rate equals to the total number of neutrons hitting the torus sample (2):

$$R_{14} = F_{th}(1 - exp\,(-x\,/\,\lambda_{th}))S = F_{th}S \qquad (2)$$

Here S is the area of the sample surface, and $(1 - exp(-x/\lambda_{th})$ determines the neutrons attenuation at distance x inside the sample. The gamma-yield caused by thermal neutrons Y_{th} is the product of capture reactions rate R_{th} and multiplicity of capture γ-rays M_{γ}. During experiments the total yield $Y_{exp}=Y_{14}+Y_{th}$ is measured including both thermal and 14-MeV neutrons induced reactions, and the enhancement of gamma-yield caused by thermal neutrons contribution can be expressed as follows (3):

$$\frac{Y_{exp}}{Y_{14}} = 1 + \frac{Y_{th}}{Y_{14}} = 1 + \frac{F_{th} S M_{\gamma}}{N_{14} F_{14} \alpha_n \sigma_{14}} \qquad (3)$$

While the measured cross section of gamma-ray production σ_{exp} is proportional to the yield Y_{exp} (because Y_{th} was normalized to $N_{14}F_{14}$), and the response function of the spectrometer is the same for gamma-rays of different origins, the relation between different gamma-production cross sections correlates with corresponding yields. The cross section discrepancy between measured experimental data and theoretical calculations in the 5÷10 MeV energy range is (4):

$$\frac{\int_5^{10} \frac{d\sigma_{exp}}{dE} dE}{\int_5^{10} \frac{d\sigma_{14}}{dE} dE} = 1.64 \pm 0.18 \qquad (4)$$

while equation (3) gives close to this discrepancy value between experimental and theoretical yields (5):

$$1 + \frac{F_{th} S M_{\gamma} N_{\gamma th}}{N_{14} F_{14} \alpha_n \sigma_{14} N_{\gamma 14}} = 1.47 \qquad (5)$$

Here $M_{\gamma}=4.1$ is average gamma-ray multiplicity of ^{113}Cd(n, γ)^{114}Cd reactions, $N_{\gamma th}=10.2\%$ is part of gamma-spectrum within considered energy range induced by thermal neutrons [11] and $N_{\gamma 14}=2.2\%$ is the same for 14-MeV neutrons obtained from Empire calculations.

The values in (4) and (5) confirm the idea of contribution from thermal neutrons to the measured spectrum. The excess of the measured gamma-production cross section within 5÷10 MeV is 60 mb, and one could assume that it is caused not by 14-MeV, but thermal neutrons interactions with ^{113}Cd nuclei. Then the cross section of gamma-ray production renormalized to the flux of thermal neutrons and number of ^{113}Cd nuclei equals 11 450 barn, which makes 12.7% of the total cross section of gamma-yield, namely 88 000 b [11].

The value obtained in (5) shows that the number of gamma-rays generated by thermal neutrons is about 47% of gamma-rays from 14-MeV neutrons and it is comparable with obtained discrepancy (4). Obviously, this contribution must be taken into account during gamma-spectra measurements from fast neutrons interactions. It can be seen from table 1 that the primary 14-MeV neutrons beam near the sample is bigger than at other locations by 30 (behind the shielding bar) and 385 (near the wall) times respectively, while the thermal neutrons flux is nearly constant regardless of the location of control volume in the experimental hall. It means that the changing of the sample position will not reduce the influence from scattered neutrons and the additional shielding is required. In particular, it can be realized with the help of neutronstop covering on walls, ceiling and floor. According to MCNP simulations, such type of shielding (with bricks of 10 cm thickness and 5% of ^{10}B addition by mass) leads to the reduction of thermal neutrons flux up to 10^2 times. But the clear gamma-spectra from 14-MeV neutrons can be obtained only taking into account the scattered ones.

Despite values in (4) and (5) are close, the experimental enhancement is still higher than expected one from thermal neutrons. This bump was also observed in the experiments with high flux of thermal neutrons and enriched ^{113}Cd sample in [11], and it could not be reproduced by theoretical calculations. So this energy region is under the interest and requires additional investigations.

Conclusions

It was shown that the discrepancy in the gamma-spectrum from natCd sample is caused by the thermal neutrons interactions due to the big capture cross section with ^{113}Cd nuclei. The MCNP simulations confirmed this idea and helped to understand the irradiation conditions of the experiment. According to obtained results, about 30% of all gamma-rays from $(n, x\gamma)$ reactions induced in the ^{nat}Cd sample caused by thermal neutrons, and the flux of them is nearly constant at different points in the experimental hall. Therefore, the measurements of fast neutrons interactions with cadmium samples must be conducted very carefully taking into account possible contributions from thermal neutrons. The best way is to ensure the irradiation conditions with minimum scattered and maximum of 14-MeV neutrons fluxes and to provide sufficient separation between them. Our further investigation includes reexamination of gamma-production cross sections of ^{nat}Cd$(n, x\gamma)$ reactions induced by 14-MeV neutrons.

References

[1] Simakov SP, Pavlik A, Vonach H, Hlavac S. Status of experimental and evaluated discrete γ-ray production at En=14.5 MeV. Vienna: International Atomic Energy Agency; 1998. 60 p.

[2] Bondar BM, Bondar VM, Gorbachenko OM, Kadenko IM, Leshchenko BYu, Onishchuk YuM, et al. Cross sections of prompt γ-ray production induced by interactions of fast neutrons with cadmium. *Nucl. Phys. At. Energy*. 2011;12(2):129-36.

[3] Bondar VM, Gorbachenko OM, Kadenko IM, Leshchenko BYu, Onishchuk YuM, Plujko VA. Spectra of gamma-rays in (n,xγ) reactions on ferrum and bismuth nuclei. *Nucl. Phys. At. Energy.* 2010;11(3):246-50.

[4] Kadenko IM, Plujko VA, Bondar BM, Gorbachenko OM, Leshchenko BYu, Solodovnyk KM. Prompt gamma-rays from fast neutron capture in ^{nat}Ni. *Nucl. Phys. At. Energy.* 2016;17(2):122-29.

[5] Kadenko IM, Plujko VA, Bondar BM, Gorbachenko OM, Leshchenko BYu, Solodovnyk KM. Gamma-rays from ^{nat}Sn and ^{nat}C induced by fast neutrons. *Nucl. Phys. At. Energy.* 2016;17(4):349-53.

[6] Herman M, Capote R, Carlson BV, Oblozinsky P, Sin M, Trkov A, et al. EMPIRE: Nuclear reaction model code system for data evaluation. *Nucl. Data Sheets.* 2007;108(12):2655-715.

[7] Bezotosnyy VM, Gorbachev VM, Surov LM, Shvetsov MS. Differential and total cross sections for gamma-production by inelastic interaction of 14 MeV neutrons with different nuclei. *PAST.* 1978;3(30):21-8.

[8] Nefedov YuYa, Nagornyj VI, Semenov VI. The experimental results of the gamma-ray production cross-section and spectra at the nonelastic interaction 14 MeV neutrons with nuclei of Na, S, Cl, Ti, V, Cr, Ni, Zn, Ge, Nb, Cd, In, Sn, Bi, ^{235}U and ^{238}U. *PAST*. 2000;(1):7-10.

[9] Rusev G, Jandel M, Krtiˇcka M, Arnold CW, Bredeweg TA, Couture A, et al. Cascade γ-rays following capture of thermal neutrons on ^{113}Cd. *Phys. Rev. C.* 2013;88(5):057602.

[10] RSICC Computer code collection. MCNP4C. Monte Carlo N particle transport code system. United States: Oak Ridge National Laboratory; 2000. 898 p.

[11] Belgya T, Szentmiklósi L, Massarczyk R, Schwengner R, Junghans AR, Grosse E. High-resolution study of the ^{113}Cd(n, γ) spectrum by statistical decay model with discrete levels and transitions. *EPJ Web Conf.* 2017;(146):05009.

Список використаної літератури

[1] Simakov SP, Pavlik A, Vonach H, Hlavac S. Status of experimental and evaluated discrete γ-ray production at En=14.5 MeV. Vienna: International Atomic Energy Agency; 1998. 60 p.

[2] Бондар БМ, Бондар ВМ, Горбаченко ОМ, Каденко ІМ, Лещенко БЮ, Оніщук ЮМ, та ін. Диференціальні перерізи вильоту гамма-квантів при взаємодії нейтронів з ядрами кадмію. *Ядерна фізика та енергетика*. 2011;12(2):129–36.

[3] Бондар ВМ, Горбаченко ОМ, Каденко ІМ, Лещенко БЮ, Оніщук ЮМ, Плюйко ВА. Спектри гамма-квантів у (*n,xγ*) реакціях на ядрах заліза та вісмуту. *Ядерна фізика та енергетика.* 2010;11(3):246–50.

[4] Каденко ІМ, Плюйко ВА, Бондар БМ, Горбаченко ОМ, Лещенко БЮ, Солодовник КМ. Миттєві гамма-кванти при поглинанні швидких нейтронів ядрами ^{nat}Ni. *Ядерна фізика та енергетика*. 2016;17(2):122–29.

[5] Каденко ІМ, Плюйко ВА, Бондар БМ, Горбаченко ОМ, Лещенко БЮ, Солодовник КМ. Гамма-випромінювання з ^{nat}Sn та ^{nat}C під дією нейтронів. Ядерна фізика та енергетика. 2016;17(4):349–53.

[6] Herman M, Capote R, Carlson BV, Oblozinsky P, Sin M, Trkov A, et al. EMPIRE: Nuclear reaction model code system for data evaluation. *Nucl. Data Sheets.* 2007;108(12):2655–715.

[7] Безотосный ВМ, Горбачев ВМ, Суров ЛМ, Швецов МС. Полные сечения образования γ-квантов при неупругом взаимодействии 14-МеВ нейтронов с различными ядрами. *Вопросы атомной науки и техники, серия ядерные константы*. 1978;3(30):21–8.

[8] Нефедов ЮЯ, Нагорный ВИ, Семенов ВИ, Житник АК, Орлов РА, Шмаров АЕ. Результаты измерений сечений и спектров образования гамма-квантов при неупругом взаимодействии 14 МэВ нейтронов с ядрами Na, S, Cl, Ti, V, Cr, Ni, Zn, Ge, Nb, Cd, In, Sn, Bi, ^{235}U and ^{238}U. *Вопросы атомной науки и техники, серия ядерные константы*. 2000;(1):7–10.

[9] Rusev G, Jandel M, Krtiˇcka M, Arnold CW, Bredeweg TA, Couture A, et al. Cascade γ rays following capture of thermal neutrons on ^{113}Cd. *Phys. Rev. C.* 2013;88(5):057602.

[10] RSICC Computer code collection. MCNP4C. Monte Carlo N particle transport code system. United States: Oak Ridge National Laboratory; 2000. 898 p.

[11] Belgya T, Szentmiklósi L, Massarczyk R, Schwengner R, Junghans AR, Grosse E. High-resolution study of the ^{113}Cd(n, γ) spectrum by statistical decay model with discrete levels and transitions. *EPJ Web Conf.* 2017;(146):05009.

Підсилення виходу гамма-квантів при взаємодії швидких нейтронів з ізотопами кадмію

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Анотація

Мета. У цій статті представлено результати дослідження збільшення виходу гамма-випромінювання від реакцій ^{nat}Cd($n,x\gamma$), що було отримано під час експерименту з нейтронами з енергією 14-МеВ, порівняно з теоретичним спектром, розрахованим у коді Empire.

Методи. Експеримент проведено з застосуванням часопрольотної методики вимірювань для n-γ дискримінації. За допомогою MCNP симуляції було виконано експеримент й оцінено вплив фону від розсіяних нейтронів на форму гамма-спектру.

Результати. Було показано, що незважаючи на часову сепарацію подій, захват теплових нейтронів ізотопом ^{113}Cd дає суттєвий внесок у гамма-спектр із реакцій ^{nat}Cd(n, $x\gamma$), зумовлених прямими DT-нейтронами. Було визначено флюенс теплових нейтронів, який виявився сталим у різних точках експериментальної зали.

Висновки. Для коректного вимірювання перерізів виходу гамма-квантів для зразків кадмію необхідно забезпечувати додаткову сепарацію між прямими та розсіяними нейтронами

Ключові слова: теплові нейтрони, DT-нейтрони, кадмій, гамма-спектр, гамма-вихід

Усиление выхода гамма-квантов при взаимодействии быстрых нейтронов с изотопами кадмия

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Анотація

Цель. В этой статье представлены результаты исследования увеличения выхода гамма-излучения от реакций ^{nat}Cd (n, $x\gamma$), что были получены в ходе эксперимента с нейтронами с энергией 14-МэВ по сравнению с теоретическим спектром, рассчитанным в коде Empire.

Методы. Эксперимент проведен с применением часопролётной методики измерений для n-γ дискриминации. С помощью MCNP симуляции было выполнено эксперимент и оценено влияние фона от рассеянных нейтронов на форму гамма-спектра.

Результаты. Было показано, что несмотря на временную сепарацию событий, восторг тепловых нейтронов изотопом ^{113}Cd дает существенный вклад в гамма-спектр с реакций ^{nat}Cd (n, $x\gamma$), обусловленных прямыми DT-нейтронами. Было определено флюенс тепловых нейтронов, который оказался устойчивым в разных точках экспериментальной залы.

Выводы. Для корректного измерения сечений выхода гамма-квантов для образцов кадмия необходимо обеспечивать дополнительную сепарацию между прямыми и рассеянными нейтронами

Ключевые слова: тепловые нейтроны, DT-нейтроны, кадмий, гамма-спектр, гамма-выход