APPLICATION OF GAMMA-SPECTROMETER ON THE BASIS OF CdTe IN DOSIMETRY OF HIGH-ENERGY BREMSSTRAHLUNG

A.A. Zakharchenko, V.E. Kutny, A.V. Rybka, V.A. Shevchenko, V.L. Uvarov, A.Eh. Tenishev, I.N. Shlyakhov

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

E-mail: uvarov@kipt.kharkov.ua

The conditions are studied of using a semiconductor gamma-spectrometer with a "warm" detector on the basis of CdTe for dosimetry support of photonuclear technologies with the use of high-energy high-power bremsstrahlung radiation. For a method of activation dosimetry based on the ^{115}In (γ,γ′) ^{115m}In reaction, the analysis and optimization of measurement conditions of an activated In-dosimeter with a CdTe-spectrometer have been conducted using a computer simulation technique. The dependence of detector sensitivity on dosimeter size has been established. It was shown, that one can to control the sensitivity of a dosimetry system within the span 1 kGy…10 MGy and higher by change the dosimeter dimensions. The conditions of measurement of activity of the ^{115m}In isomer on the samples from natural indium by the instrumentality of a CdTe-spectrometer were investigated. A procedure of the activation dosimeter calibration was discussed

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INTRODUCTION

Last years considerable advance is observed in development of photonuclear technologies using high-power bremsstrahlung (X-ray) radiation with spectrum end-point energy up to 100 MeV. Non-reactor isotope production, in the first place, of Tc-99m (see, e.g. [1]), control with a sub-critical assembly using an electron accelerator [2] and oth. are among such technologies. For one operation run, the target devices of those plants obtain absorbed dose of radiation of up to ~ megagrey and still more. At the same time, the available standardized dosimetry methods are of little use for those irradiation regimes.

In the work [3], a technique of activation dosimetry of high-energy high-power X-ray was proposed. The method is based on application of a reference photonuclear reaction, which yield in a target-dosimeter meets the condition

$$\dot{A} = \eta D, \qquad (1)$$

where D – is the absorbed dose in the target; $\dot{A}$ – is the specific activity of the target against a nuclide-product of the reference reaction; η – is the coupling factor. So it has been shown, that the ^{115}In (γ,γ′) ^{115m}In reaction having a low energy threshold of 1.078 MeV, can be used as a reference one. In particular, it was established experimentally, that at end-point energy of the X-ray photons of up to 70 MeV the η factor changes little and makes ≈4 Bq·g^{-1}·Gy^{-1}. The calculations have shown, that this feature remains in force at a photon energy of up to 100 MeV as well. At the same time, a perfect inconvenience of the method is the necessity to measure the activity of the ^{115m}In isomer ($T_{1/2}$ = 4.4 h; E_γ = 336.24 keV) by the instrumentality of a semiconductor detector cooled with the liquid nitrogen.

In the work, the conditions of application of a "warm" spectrometer for activation dosimetry are studied.

1. MEASUREMENT TECHNIQUE

A spectrometer Amptek XR-100T (Amptek, USA) with a detector on the basis of a CdTe single crystal by 3×3×1 mm in dimensions was used for measuring activity of the indium based dosimetry systems. The detector is located in a cylindrical casing with an input window 10 μm thick from beryllium. To decrease the self-noise, the detector is cooled up to -40°C with a Peltier refrigerator.

A feature of that type detectors is an abrupt decrease of their registration efficiency at energy of gammas E_γ>100 keV (Fig. 1). So the preliminary analysis and optimization of measurement conditions of the In-dosimeters were conducted by a computer simulation technique using a transport code GEANT4.

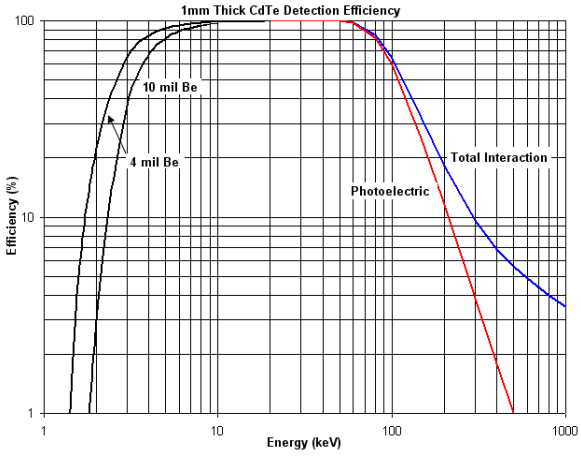


Fig. 1. Dependence of CdTe registration efficiency on energy of gammas

A simulated measurement circuit (Fig. 2) comprises the In-dosimeter in the form of a disk by d mm in diameter and L mm thick with the uniformly distributed ^{115m}In nuclei over the volume. The CdTe-detector, which registers the energy and type of the incident particles (Fig. 3), is positioned at a distance of 1mm from the disk.

As it is seen in Fig. 3,a, apart from the gammas with energy 336.24 keV, the characteristic X-ray photons with energy 24.2 and 27.2 keV, generated by the formers in indium, incident on the detector as well.

The calculation with the usage of a XMuDat package [4] has shown, that the free range of photons with energy 336.24 keV in indium makes 0.98 cm. The GEANT4 based simulation has shown, that at the in-

crease of thickness of the uniformly activated dosimeter up to 4…5 mm, the yield of γ-radiation steadily grows (Fig. 4). The further rise of dosimeter thickness results in abrupt increase of a "dead layer "of the dosimeter. The Compton electrons escaping it adversely affect the "signal-to-noise" ratio of the detector.

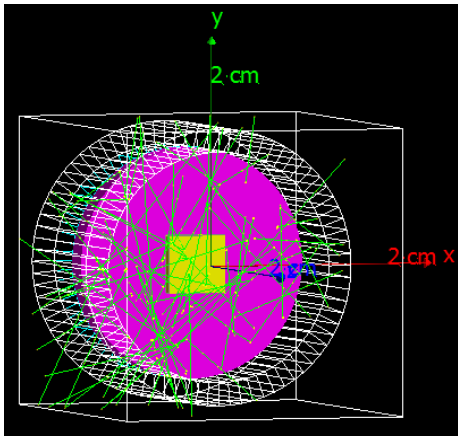
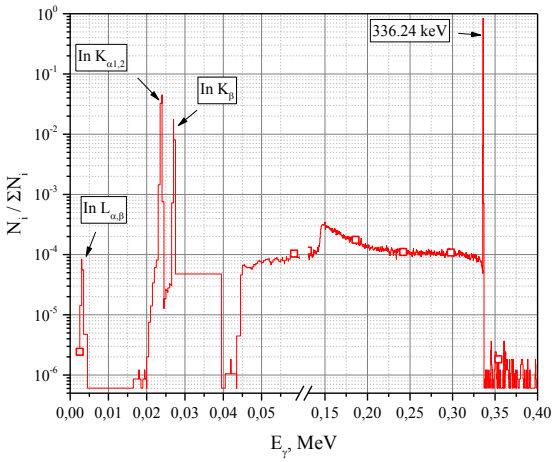
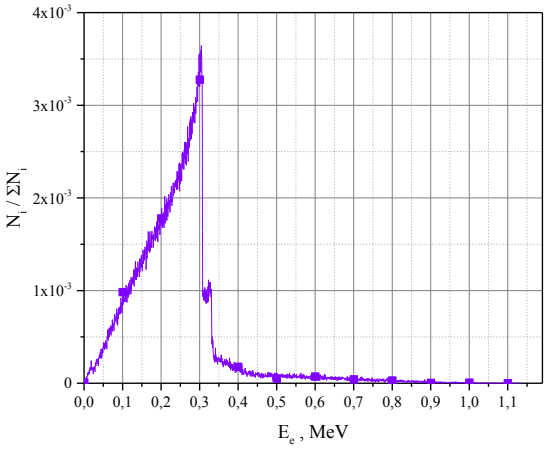


Fig. 2. Model of radiation registration with CdTe-detector



a



b

Fig. 3. Spectra of photons (a) and electrons (b) incident on the detector

In Fig. 5, a calculated spectrum at the exit of a CdTe-detector induced by radiation of the ^{115m}In isomer is presented. Taking into account, that the average energy of the electron-hole generation in CdTe is 4.43 eV, the non-equilibrium charge created in the detector at scattering into the photopeak of γ-quantum with energy 336.24 keV makes $1.22 \cdot 10^{-14}$C. The clear-cut photopeak from the gammas with energy 336.24 keV is observed.

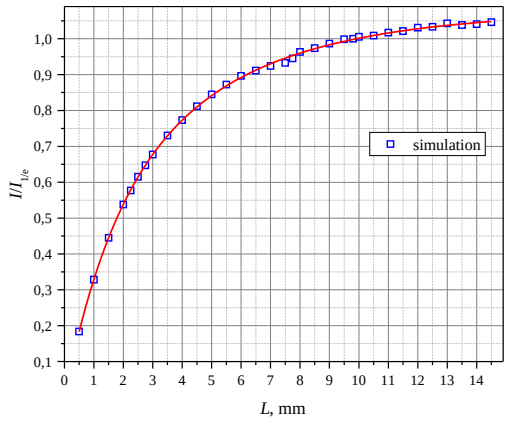


Fig. 4. Dependence of relative yield of gammas from activated In-dosimeter on its thickness

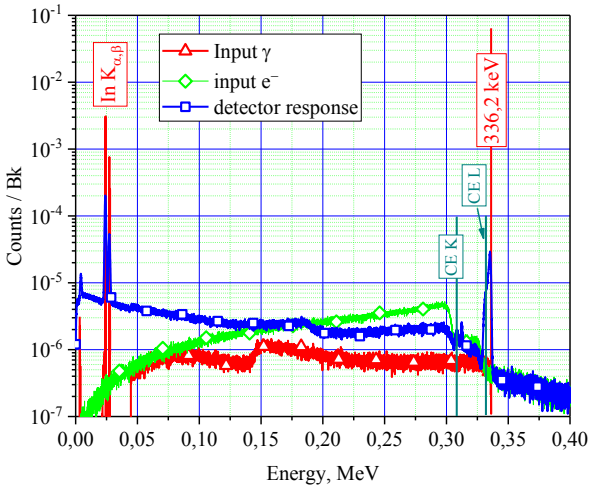


Fig. 5. Response of CdTe-detector to ^{115m}In-radiation

To study the affect of dosimeter size on the characteristics of the detector response, the dependence of the photopeak 336.24 keV amplitude and area on the dosimeter diameter has been calculated (Fig. 6). For comparison, the data on the registration conditions for ^{133}Ba are given also. That isotope has got the energy of main radiation line of 356 keV, the most close to the ^{115m}In line, and enters commonly into a kit of the reference γ-sources used for γ-spectrometer calibration. As it is follows from the data in Fig. 6, the increase of the source diameter in range 1 to 5 mm at conservation of its total activity results in reduction of detection efficiency by 30%.

In Tabl. 1, the results of calculation of characteristics of the In-dosimeters with various diameter d and thickness L are shown. The values of the absorbed dose (activity) were chosen to provide the pulse rate in the photopeak of 10 s^{-1} at EOB. That ensures a reasonable value of the statistical uncertainty.

The 10^8 cases of the ^{115m}In decay were simulated for each geometry of a radiation source. The calculated quantities were reduced to 1 Bq of the source activity. The following conventional signs are used for the quantities given in Tabl. 1.

Input 336 is the number of quanta with energy 336.24 keV entering a detector, Detection efficiency is the registration efficiency of them, Abs. eff. is the absolute detector registration efficiency of gammas with energy 336.24 keV emitted with an activated dosimeter, Act. 10-is the dosimeter activity providing the pulse rate

of 10 s^{-1} in the photopeak 336.24 keV, X-ray dose-is the absorbed dose of the bremsstrahlung radiation in a dosimeter providing its above activity.

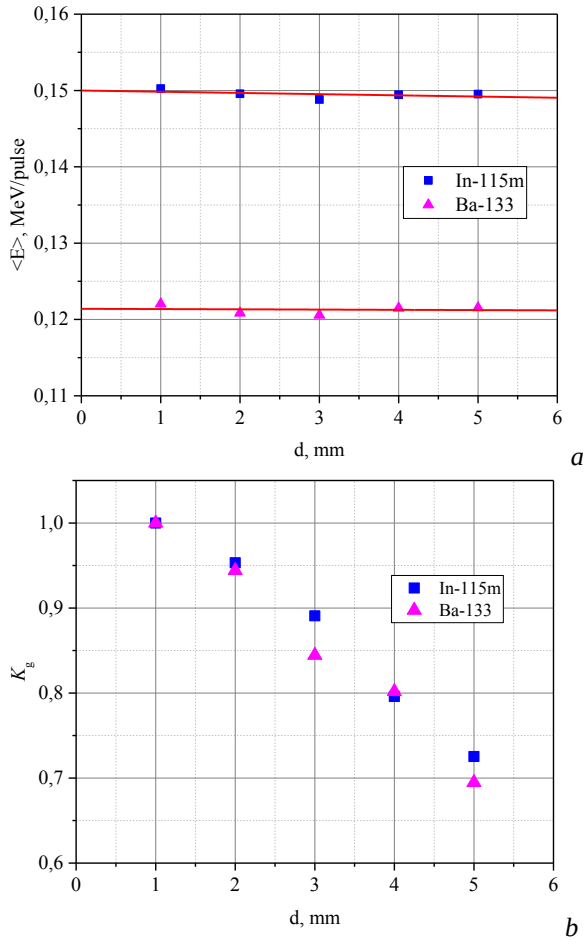


Fig. 6. Dependence of mean pulse amplitude (a) and relative photopeak area (b) on diameter of In-dosimeter

Table 1

Characteristics of In-dosimeters

Size dxL, mm	2×1	4×2	6×3	8×4	10×5
Mass, g	0.023	0.184	0.620	1.470	2.871
Input 336, quantum/Bq	0.064	0.040	0.0261	0.018	0.013
Detection efficiency, %	2.75	2.76	2.89	3.02	3.15
Abs. eff., %	0.18	0.11	0.08	0.05	0.04
Act. 10, kBq	5.69	9.01	13.24	18.37	24.31
Specific act., kBq·g^{-1}	248	49.0	21.4	12.5	8.5
X-ray dose, kGy	61.9	12.3	5.3	3.1	2.1

As it is follows from comparison the data in Tabl. 1 and Fig. 6, the dosimeter absolute registration efficiency as well as the upper limit of the span of the measured dose can be increased by reduction of detector size by up to ~10 MGy and still more.

2. ACTIVATION OF In-DOSIMETER

Bremsstrahlung radiation is commonly obtained by converting an electron beam with the use of a high-Z target (Ta, W and oth.). If the end-point energy of the beam energy spectrum is higher than the threshold of a (γ,n) reaction in the converter material, the high-energy X-ray photons induced a neutron flux escaping the converter. For instance, at using a Ta-converter and electron energy higher 7.6 MeV, the reaction $^{181}Ta(\gamma,n)^{180}Ta$ ($T_{1/2}$=8.15 h) can be appeared. As a result, alongside with the X-ray flux, which axes coincides with the one of the primary electron beam, a quasi-isotropic photoneutron flux is emitted.

The main reaction in the natural indium containing the two stable isotopes (^{115}In (95.7%) and ^{113}In (4.3%)) in the mixed X, n-radiation are given in Tabl. 2.

Table 2

Reactions in indium under the influence of X,n-radiation

Reaction	Threshold, MeV	Product identific. line, keV	$T_{1/2}$
$^{115}In(\gamma,\gamma')^{115m}In$ $^{115}In(n,n')^{115m}In$	1.078 0.44	336.24	4.49 h
$^{115}In(\gamma,n)^{114m}In$ $^{113}In(n,\gamma)^{114m}In$	9.0 -	190.27	49 day
$^{113}In(\gamma,\gamma')^{113m}In$ $^{113}In(n,n')^{113m}In$	0.132 -	391.69	99.4 min
$^{113}In(\gamma,n')^{112m}In$	9.4	156.40	20.9 min
$^{115}In(n,\gamma)^{116m}In$	-	416.86	54.3 min

Activation of In-dosimeters was carried out at a LU-10 electron Linac of NSC KIPT [5]. The accelerator has got at its exit a vertical beam scanner commonly used for industrial product processing, as well as a kid of measuring devices for the on-line diagnostics of main beam parameters [6].

The schematic of the dosimeter activation are shown in Fig. 7. A bremsstrahlung radiation converter C in the form of a 2.4 mm thick tantalum plate with the one-through water cooling was placed behind an exit window of the accelerator. The converter was followed by a filter F (an electron stopper comprising 4 Al-plates each by 2 mm in thickness). At a distance of 20 cm from the converter, a target T! consisting of the In-samples, and also the strips of a dosimetry film B3 (GEX Corp., USA) was positioned. A target T2 of similar content was located at same distance from the converter but 90° angularly relative to the electron beam axes. Such configuration of the exit devices provided the possibility to assess the contribution of neutron channels into indium activation.

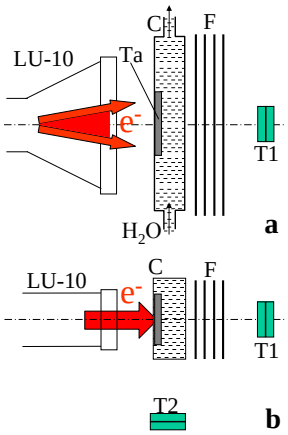


Fig. 7. Geometry of In-dosimeters activation: a – side view; b – plan view

The In-dosimeter irradiation was conducted for 1-h at a beam energy in spectral maximum of 11.2 MeV, average beam current of 450 μA and width of the scanning zone at the converter of 12 cm.

The absorbed dose in the target T1 measured with the B3 film maid 120 kGy. After a period t = 30 min, the targets were transferred to a γ-spectrometer for measuring their activity. In Fig. 8, the spectra of the activated T1 dosimeter measured in various periods after EOB are given. For comparison, a spectrum obtained using a "cold" Ge(Li)-detector is presented in Fig. 8,c.

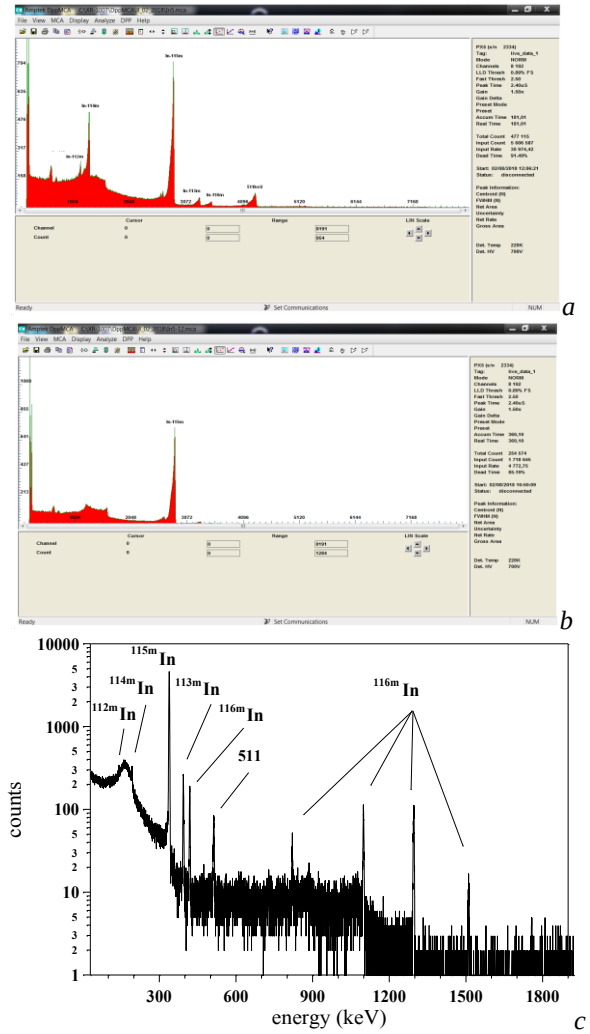


Fig. 8. Spectra of activated In-dosimeter: a – CdTe, t=34 min; b – CdTe, t=5 h; c – Ge(Li), t=2.78 h

3. DISCUSSION

As it follows from the data in Tabl. 1, the absolute registration efficiency decreases with the grows of size of an indium sample because a greater part of the quanta miss the detector. The increase of the intrinsic registration efficiency is connected with the rise of gammas cutting the detector surface at an angle considerably less than 90°. That enlarges an effective thickness of a CdTe-detector for such gammas, as well as the probability of scattering them into the photopeak.

As the absolute registration efficiency for the large samples goes down, the sample activity grows to be need for providing the count rate in the photopeak of $10\ s^{-1}$. At the same time, the specific activity of a dosimeter decreases because the sample mass grows higher than its area facing the detector.

Comparison of T1 and T2 spectra shows the coincidence of 416.86 keV photopeaks. That testifies the closeness of neutron flux incident on the each target. At the same time, the amplitude of the 336.24 keV peak in the spectrum of the T2 target does not exceed 2…3% its value in the target T1. That ratio determines the upper estimate for the contribution of (n,n′) channel into the ^{115m}In yield.

Determination of absorbed dose by activation technique can be maid by means of measuring the activity in a target-dosimeter generated through a reference reaction with the use the formula

$$D = \frac{\lambda N(E_\gamma) e^{\lambda t}}{\eta m \varepsilon(E_\gamma) P(E_\gamma)(1-e^{\lambda T})(1-e^{-\lambda \tau})} \cdot \frac{\mu L}{(1-e^{-\mu L})}, \quad (2)$$

where $N(E_\gamma)$ – is the number of counts in a photopeak with energy E_γ, for counting time τ; λ – is the decay constant of a nucleus-product of the reference reaction; $\varepsilon_\gamma(E_\gamma)$ – is the detector registration efficiency of gammas with energy E_γ; $P(E_\gamma)$ – is the branching of gammas with energy E_γ; T – is the period of the target activation, μ – is the linear attenuation coefficient of photons with energy E_γ in a target material.

Calibration of activation dosimeters against the absorbed dose can be carried out with the use of a standardized reference dosimeter at a dose of D_{cal} within its specified dose span. In this case, the dose obtained by activation dosimeter can be determined using the expression

$$D = D_{cal} \frac{N(E_\gamma)}{N(E_\gamma)_{cal}} \cdot \frac{e^{\lambda(t-t_{cal})}(1-e^{-\lambda T_{cal}})(1-e^{-\lambda \tau_{cal}})}{(1-e^{-\lambda T})(1-e^{-\lambda \tau})}, \quad (3)$$

where the quantities with the subscript "cal" are related to a calibration regime, when the ones without the subscript – to the conditions of the dose measurement by the activation technique.

CONCLUSIONS

A "warm" γ-spectrometer with a CdTe-detector can be used for measuring the absorbed dose of the high-energy X-ray radiation by the activation technique on the basis of natural indium in the range ~1 kGy…10 MGy with ensuring a strictly linear dependence between the absorbed dose and the specific activity of the ^{115m}In isomer. The sensitivity of a dosimetry system can be readily changed by option of mass of an In-sample and does not depend on its aggregate state and the ambient conditions. After "cooling" the In-dosimeter can be unrestrictedly reused.

Calibration of the proposed dosimeters can be fulfilled in accordance with the standartized procedures ordinary used when measuring the γ-activity and absorbed dose (see, e.g. [7, 8]).

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ПРИМЕНЕНИЕ ГАММА-СПЕКТРОМЕТРА НА ОСНОВЕ CdTe В ДОЗИМЕТРИИ ВЫСОКОЭНЕРГЕТИЧНОГО ТОРМОЗНОГО ИЗЛУЧЕНИЯ

А.А. Захарченко, В.Е. Кутний, А.В. Рыбка, В.А. Шевченко, В.Л. Уваров, А.Э. Тенишев, И.Н. Шляхов

Исследованы условия применения п/п гамма-спектрометра с «теплым» детектором на основе CdTe для дозиметрического сопровождения фотоядерных технологий с использованием высокоэнергетичного тормозного излучения большой мощности. Для метода активационной дозиметрии на основе реакции ^{115}In (γ,γ′) ^{115m}In с помощью компьютерного моделирования выполнены анализ и оптимизация условий измерения CdTe-спектрометром активированного In-дозиметра. Определена зависимость чувствительности детектора от размеров дозиметра. Показано, что путем их изменения можно изменять чувствительность дозиметрической системы в диапазоне ~1 кГр…10 МГр. Экспериментально исследованы условия измерения активности изомера ^{115m}In в образцах из природного индия с помощью CdTe-спектрометра. Обсуждается процедура калибровки активационных дозиметров.

ЗАСТОСУВАННЯ ГАММА-СПЕКТРОМЕТРА НА ОСНОВІ CdTe У ДОЗИМЕТРІЇ ВИСОКОЕНЕРГЕТИЧНОГО ГАЛЬМІВНОГО ВИПРОМІНЮВАННЯ

О.О. Захарченко, В.Є. Кутний, О.В. Рибка, В.А. Шевченко, В.Л. Уваров, А.Е. Тєнішев, І.М. Шляхов

Досліджено умови застосування н/п гамма-спектрометра з «теплим» детектором на основі CdTe для дозиметричного супроводження фотоядерних технологій з використанням високоенергетичного гальмівного випромінювання великої потужності. Для методу активаційної дозиметрії на основі реакції ^{115}In (γ,γ′) ^{115m}In за допомогою комп'ютерного моделювання виконані аналіз і оптимізація умов вимірювань CdTe-спектрометром активованого In-дозиметра. Визначена залежність чутливості детектора від розмірів дозиметра. Показано, що шляхом їх зміни можна змінювати чутливість дозиметричної системи в діапазоні ~1 кГр…10 МГр. Експериментально досліджені умови вимірювання активності ізомеру ^{115m}In в зразках з природного індію за допомогою CdTe-спектрометра. Обговорюється процедура калібрування активаційних дозиметрів.