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RADIOBIOLOGY, ECOLOGY AND NUCLEAR MEDICINE

# Dosimeter for Measuring the Ambient Dose of Neutrons with Energy from $10^{-4}$ MeV to 1 GeV Based on a Heterogeneous Moderator

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**Abstract**—The construction of a dosimeter for measuring the ambient dose of neutrons with energy from $10^{-4}$ MeV to 1 GeV based on a cylindrical polyethylene moderator with lead and cadmium inserts and a $^3$He counter of thermal neutrons is proposed. Numerical Monte Carlo simulations based on the GEANT4 and SHIELD programs were applied to choose the optimal design of the dosimeter and calculate its energy sensitivity function. The device can be used for operational and stationary radiation monitoring in neutron fields on high-energy accelerators. A comparison of the dosimeter characteristics with foreign analogs is given.

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## INTRODUCTION

Measuring the dose of neutrons with energies exceeding 10–15 MeV is one of the most important and relevant problems of ensuring radiation safety at high-energy particle accelerators, since the contribution of these neutrons to the total dose of radiation beyond the radiation shield of the accelerator can be significant (up to tens of a percent); at the same time, the overwhelming majority of domestic and foreign neutron dosimeters are intended for application in the nuclear power industry or in the fields of isotope neutron sources, where neutron energy does not exceed 10 MeV, which determines the principle of their operation and operational energy range.

The problem of monitoring the neutron fields around the NICA accelerating complex is aggravated by the fact that the boundary of its sanitary protective zone (SPZ) in some places is close to radiation sources, and, according to the normative documents [1, 2] and the collider design [3], 1 mSv (the limit of annual effective dose for population) should be ensured on its SPZ boundary. The radiation dose at a distance from high-energy accelerators is mainly determined by "skyshine" neutrons with wide-band energy range. In this respect, the reliability of measuring neutron doses around the NICA accelerating complex is subject to strict requirements.

The configuration of a typical neutron dosimeter includes a hydrogenous (generally, polyethylene) moderator 20–25 cm in diameter with a slow neutron detector inside. Proportional $^3$He or boron-containing counters (with amorphous boron or $BF_3$ gas) are mostly used as slow neutron detectors. The functions of the energy dependence of the sensitivity of these dosimeters sharply decrease when neutron energy exceeds 10–20 MeV, which makes them useless for dose measuring in the hard neutron fields.

It is basically possible to increase the moderator size (a spherical moderator up to 18 inches in diameter is known to be used) to register high-energy neutrons; however, in practice, such a dosimeter is rather inconvenient in application. Another option is to use a heterogeneous moderator composed of polyethylene and a layer of heavy metal (converter) that dissipates the energy of neutrons involved in nuclear reactions, in addition to neutron thermalization due to elastic scattering from hydrogen in polyethylene. The converter can be applied either as an external shell of the moderator or in the form of its internal insert. The second option is more preferable, since all secondary neutrons leaving the converter within 4π mr undergo thermalization in polyethylene. An efficient converter should have a large cross section of n-A interactions and a small cross section of neutron absorption. In this regard, tungsten demonstrates the best properties.

Here, LINUS [4] and WENDI-II [5] dosimeters with effective range extending to 1 GeV are examples of the application of this type of converter. Unfortunately, their availability is limited and their cost is rather high due to the W-converter.

## 1. HIGH-ENERGY NEUTRON DOSIMETER WITH A LEAD CONVERTER

In this paper, the creation of a high-energy neutron dosimeter with lead converter is considered. As a material of the converter, lead is much cheaper and more technological than tungsten, thus providing the opportunity to manufacture these dosimeters at production facilities of the Joint Institute for Nuclear Research (JINR).

In order to measure the ambient doses (ambient equivalent of a dose) of neutrons adequately by a dosimeter, the dosimeter design should be aimed at making the energy dependence of its sensitivity function (SF) similar to the energy dependence of the sensitivity function of the specific ambient dose (measured at neutron unit fluence) $h^*(10, E)$ [6] (ideally, they should be linearly dependent). Ambient dose H*(10) is recommended by the International Commission on Radiological Protection [7] as a measurand, in contrast to the effective dose accepted for the environmental monitoring and in radiation zones, and is a conservative estimation of the effective dose in a wide range of neutron energies. In order to measure the ambient dose, the neutron field should be homogeneous within the limits of the detector sensitive volume, and the detector should have isotropic sensitivity. Dose H*(10) of a neutron spectrum is calculated as

$$\mathrm{H}^*(10) = \int \Phi(E) h^*(10, E) dE, \quad (1)$$

where $E$ is the neutron energy and $\Phi(E)$ is the neutron spectrum.

If the dosimeter sensitivity function $R(E)$ is high, close to $h^*(10, E)$, i.e.. $CR(E) \approx h^*(10, E)$, the ambient dose is approximately determined by multiplying its SF by normalization factor $C$:

$$\mathrm{H}^*(10) \approx \int CR(E)\Phi(E) dE. \quad (2)$$

In practice, the normalization (determining C) is made during the dosimeter graduation in the field of standard sources of neutrons with the known spectrum. The calculated values of $R(E)$ presented in this paper are normalized to $h^*(10, E)$ at neutron energy 2 MeV close to the mean energy of the neutrons from $^{252}$Cf source.

The form of function $R(E)$ depends on the dosimeter design: its geometry, moderator, and converter materials; the inclusion of additional elements to change the form of $R(E)$ (for example, cadmium layer); etc. The dosimeter simulation stipulated variations of the polyethylene layer thickness and of the converter material and thickness; the influence exerted by the cadmium layer and the configuration around the converter were also considered.

The experience of designing neutron dosimeters shows that it is impossible to provide good similarity of function $R(E)$ to function $h^*(10, E)$ over the whole range of neutron energies from thermal to 1 GeV (11 orders of energy values) due to the fact that the physical processes of interactions with substance of neutrons with very different energies differ greatly. Therefore, it was considered expedient to achieve the maximum similarity of functions in the field of neutrons with energies higher than 0.1 keV, since the contribution of lower energy neutrons to the dose, as is observed in the spectra of neutrons beyond the radiation shield and in scattered fields around high-energy accelerators, is negligibly small. Thus, in [8], it is shown that, according to the neutron spectra at distances of 50 and 100 m from the Nuclotron center, the share of neutrons with energies even less than 10 keV in the ambient dose is 1.3 and 1.4 percent.

The dosimeter was constructed under the assumption that most of the radiation was to descend on the device laterally. During measurements in the environmental radiation fields, the geometry of irradiation of the dosimeter can be close to the isotropic geometry in the upper section. No preferential irradiation of the dosimeter from below was supposed.

## 2. MODELING THE DOSIMETER

Model calculations for different dosimeter configurations were made to demonstrate the influence of the configuration on sensitivity functions for neutron energies up to 1 GeV. The base dosimeter configuration was chosen in the form of a cylinder with approximately equal diameter and height (22.9 and 23.5 cm, respectively), which was a compromise between the technological effectiveness and the required isotropy of the detector. A heterogeneous dosimeter consists of a moderator (polyethylene with $\rho$ = 0.92 g/cm$^3$), a lead converter ($\rho$ = 11.35 g/cm$^3$), a cadmium layer, and a proportional $^3$He counter registering slow neutrons. The main response of slow neutrons with $^3$He is the exothermic reaction: $n + {}^3\mathrm{He} = p + {}^3\mathrm{H}$, the cross section of which decreases with the decrease in neutron energy inversely to its velocity. Energy $E$ = 764 keV released during the reaction is distributed between the proton and the triton inversely to their masses. Each reaction event is accompanied by a pulse formed by the counter. Another reaction registered by the counter is the neutron elastic scattering from the $^3$He nucleus with a constant cross section in a wide range of energies. When neutron energies exceed a few megaelectronvolts, inelastic reactions $n + {}^3\mathrm{He}$ start generating deuterons that are also able to make their contribution to the detector counting. Cross sections of the neutron reactions with $^3$He are shown in Fig. 1.

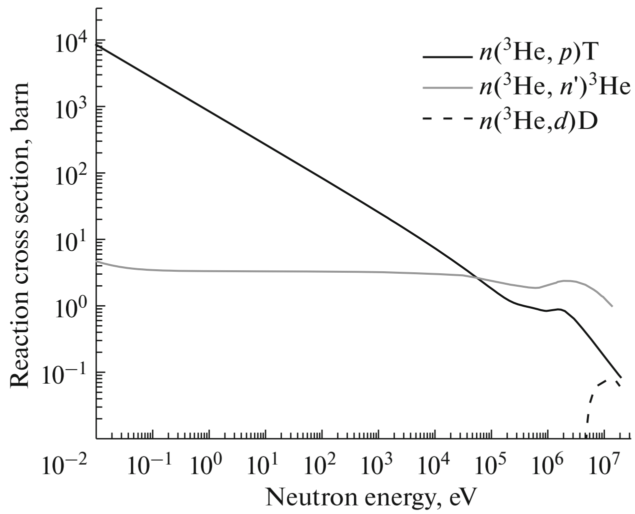


**Fig. 1.** Cross sections of neutron reactions with $^3$He.

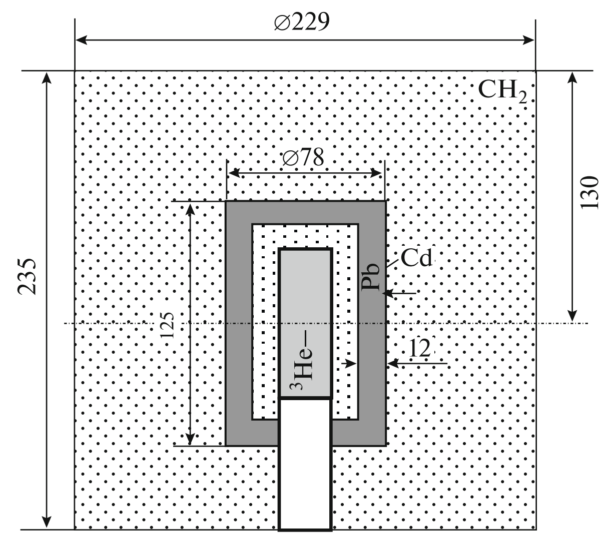


**Fig. 2.** Schematic cross section of the dosimeter.

The stopping power of $^3$He is not high; therefore, producers sometimes admix heavy inertial gases Ar or Kr to it in order to reduce proton and triton paths, not always informing users about this admixture in technical specifications, since inertial gases do not influence the sensitivity of counters when using them for slow neutron registration (at neutron elastic scattering from Ar and Kr, the energy of recoil nuclei is too low to create a pulse on the counter). However, at high neutron energies, the channels of neutron inelastic reactions with nuclei of impurities open up and produce charged particles, which can be registered by the counter. When modeling a dosimeter, the assumption was made that its slow neutron detector was a cylindrical counter with an active diameter of 24.4 mm (with 0.5-mm stainless-steel walls) and active length of 76.2 mm filled with pure $^3$He under pressure of 5 atm.

The GEANT4 software package (version 10.03. p02) [9] was used for modeling the dosimeter configuration and calculating its SF. Upon interaction with neutrons with energies of 0.025 eV to 20 MeV, the program engages tables of experimentally measured G4NDL cross sections based on rated neutron data ENDF/B-VII. In the field of neutron energies less than 4 eV, the neutron interactions with hydrogen were calculated applying the thermal model considering neutron interaction with chemically bound atoms of hydrogen. Binary Cascade, the intranuclear cascade model, was used to describe high-energy (20 MeV to 1 GeV) neutron interactions with matter.

Based on calculations aimed at optimizing the dosimeter configuration, the following parameters were chosen: the external polyethylene moderator was a cylinder 11.43 cm in radius and 23.5 cm in height having an insert of a 1.2-cm-thick and 12.5-cm-high cylindrical lead layer with an external radius of 3.9 cm. The lead converter is coated with a 0.7-mm-thick cadmium layer ($\rho = 8.65$ g/cm$^3$) to enhance the absorption of resonance and thermal neutrons. The dosimeter schematic cross section is presented in Fig. 2.

### *2.2. Calculation of the Dosimeter Sensitivity Function*

In order to calculate the dosimeter SF configuration, the geometry of dosimeter lateral irradiation and its irradiation from above by a plane homogeneous field of monoenergetic neutrons was considered within the energy range from 0.1 keV to 1 GeV. The number of charged particles (protons, deuterons, and tritons) generated inside the counter active volume in all reactions with $^3$He was determined (no energy threshold of particle registration was set, i.e., a generation event of a charged particle initiated the event of pulse registration by the counter). Similarly, it was assumed that every event of a neutron elastic scattering from $^3$He initiated a pulse registration by the counter due to gas ionization by a recoil nucleus. Other than the charged particles generated by neutrons in the counter itself, there is also a contribution of events initiated by charged particles generated by neutrons in the dosimeter materials outside the counter and registered by it. The calculations have shown that, over the whole energy range of neutrons descending on the dosimeter, reaction $n(^3\text{He}, p)^3\text{H}$ makes the main contribution to the number of registered events. No other process contribution exceeded 1.5%, so they were not considered in our further calculations within the result analysis.

In order to choose the optimum thickness of the lead converter, calculations of thicknesses of the converter lateral walls and its end-face of 8 to 15 mm were

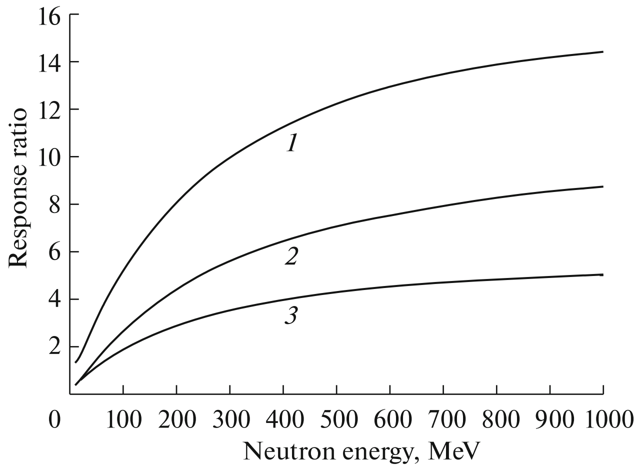


**Fig. 3.** Ratio of responses from dosimeters with 1.2-cm-thick converters made of lead (*1*), tungsten with a density of 19.3 g/cm$^3$ (*2*), and tungsten with a density of 10.62 g/cm$^3$ (*3*) to the response of a dosimeter without a converter.

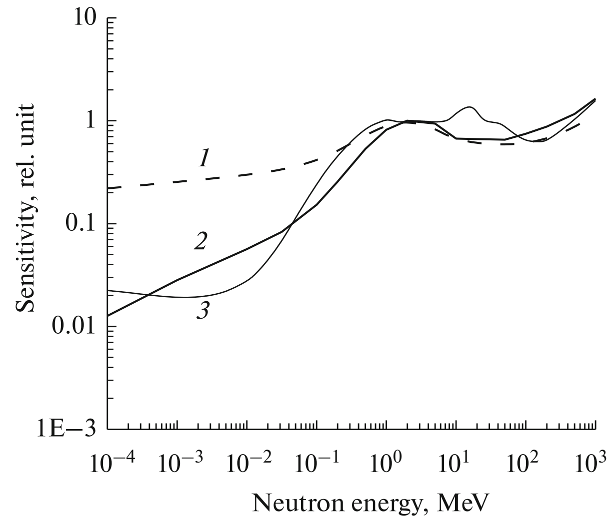


**Fig. 4.** Sensitivity of the dosimeter upon lateral irradiation by neutrons without a cadmium layer (*1*) and with a 0.7-mm-thick cadmium layer (*2*) around the lead converter; (*3*) function $h^*(10, E)$ (normalization at 2 MeV).

made, keeping the thicknesses of external and internal layers of the polyethylene moderator. The thickness of the lead converter influences the relation between the number of neutrons that have undergone nuclear interactions in the converter and the number of neutrons thermalized due to elastic collisions with the moderator hydrogen; i.e., it determines the contribution of different mechanisms to the neutron energy dissipation and, thus, changes the spectrum of neutrons penetrating into the $^3$He counter. Finally, the thickness of lead layer was chosen to be 12 mm, at which the satisfactory agreement between the dosimeter SF and the energy dependence of specific ambient dose in the field of neutron energies exceeding 10 MeV was attained. A further increase in the thickness of the lead layer adds little to the SF influence, but increases the dosimeter weight. For the chosen configuration of the converter, the total weight of the dosimeter is about 13 kg.

A version of dosimeter configuration with a 1.2-cm-thick tungsten converter with densities $\rho$ = 19.3 g/cm$^3$ and $\rho$ = 10.62 g/cm$^3$ (corresponding to the density of the WENDI-II dosimeter converter made by the powder metallurgy technique) was considered without cadmium around the converter and with lateral irradiation of the dosimeter. In Fig. 3, the ratios of responses from dosimeters with different converters (W and Pb) to the response of a dosimeter without a converter are presented for neutron energies exceeding 10 MeV. The maximal value of the response is obtained with the lead converter of neutrons in the field of energies exceeding 10 MeV. The total cross sections of neutron interactions with tungsten and lead in the field of high-energy neutrons are approximately the same, and the thermal neutron capture cross section of lead is considerably less than that of tungsten.

The insertion of a cadmium layer improves $R(E)$ in the field of energies lower than 1 MeV. In Fig. 4, in the absence of cadmium, a considerable difference between the forms of sensitivity function $R(E)$ of the dosimeter and $h^*(10, E)$ is apparent. The application of a 0.7-mm-thick cadmium layer around the lead converter with the thickness of 1.2 cm provides the optimal value of $R(E)$ in the range of neutron energies $10^{-4}$–$10^3$ MeV.

The choice of the physical model of neutron interaction with matter can also influence the calculations of function $R(E)$. However, there are negligible differences between the calculations made within the Binary Cascade model in combination with the thermal model for polyethylene and slow neutrons and the calculations using the Bertini model that has been considered more preferable for a description of neutron interaction with heavy substances, except the field of energies exceeding 20 MeV, where the Bertini model presents rather higher (by ~10%) values of $R(E)$.

Additionally, the dosimeter sensitivity function at the lateral irradiation by neutrons was calculated by means of SHIELD software [10], which made it possible to simulate the neutron interaction with matter within the energy range up to 1 TeV. In order to calculate the neutron interaction with matter with energies of ≥14.5 MeV and up to 1 GeV, the software used the cascade model of nuclear reaction based on the Dubna model of intranuclear cascades [11]. The transport of neutrons with energy less than 14.5 MeV was simulated in SHIELD on the basis of 28-group system of neutron constants BNAB [12]. The comparison of dosim-

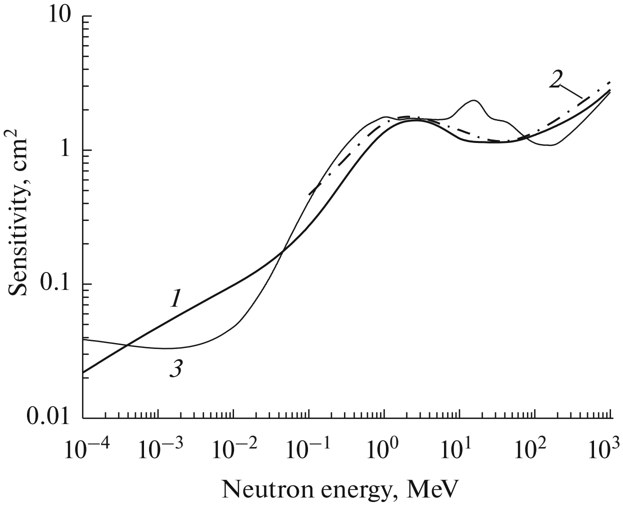


**Fig. 5.** Comparison of the dosimeter sensitivities upon lateral irradiation by neutrons: (*1*) sensitivity calculated by GEANT4 software, (*2*) sensitivity calculated by SHIELD, and (*3*) function $h^*(10, E)$ (normalization at 2 MeV).

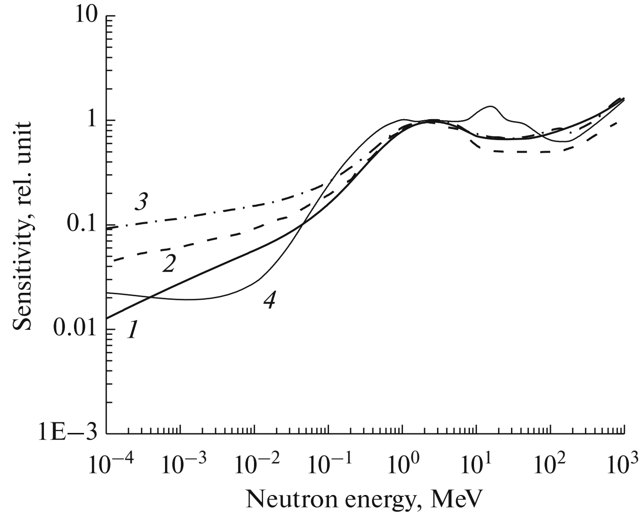


**Fig. 6.** Comparison of sensitivity functions $R(E)$ of dosimeters upon lateral irradiation by neutrons: (*1*) sensitivity function of the dosimeter proposed in this paper, (*2*) function of sensitivity of the LINUS dosimeter, (*3*) sensitivity function of the WENDI-II dosimeter, and (*4*) function $h^*(10, E)$ (normalization at 2 MeV).

eter SFs obtained by means of GEANT4 and by SHIELD shows very good agreement between the two sensitivity functions for neutrons with energies higher than 0.1 MeV (Fig. 5).

The statistical error of sensitivity functions calculated did not exceed 5%.

### *2.3. Comparison of the Proposed Dosimeter with WENDI-II and LINUS Dosimeters*

The dosimeter configuration proposed in this paper provides a satisfactory measurement of the ambient dose of neutrons over the range of $10^{-4}$–$10^3$ MeV, except the energy fields of ~$4 \times 10^{-3}$, 0.2, and 20 MeV, where the maximal differential error is about 200%. In Fig. 6, the sensitivity function of the proposed dosimeter is compared with commercially available WENDI-II and LINUS dosimeters. All functions are normalized to the same value at the neutron energy of 2 MeV, which corresponds to the requirements of neutron graduation by means of neutron source $^{252}$Cf.

The comparison shows that SF of the dosimeter proposed in this paper generally agrees with function $h^*(10, E)$ much better than those of WENDI-II and LINUS dosimeters over the entire range of neutron energies.

Measurements made near the lateral part of accelerator radiation shield showed that radiation is preferentially directional; therefore, as was mentioned above, it was a question of lateral irradiation of the dosimeter. However, a dosimeter SF depends on the angle of incidence of neutrons on it, despite the fact that dosimeters are made, whenever possible, isotropic. In Fig. 7, the SF of a dosimeter at its edge irradiation by neutrons is shown for comparison.

When the edge irradiation is directed from above, value $R(E)$ noticeably increases in the field of neutron energies exceeding 10 MeV (1.5–1.9 times on the average). However, considering the SF decrease in the energy range of 10–100 MeV, as compared with $h^*(10, E)$ at lateral irradiation of the dosimeter, this fact does not cause significant errors in measurements, even in the isotropic field of irradiation.

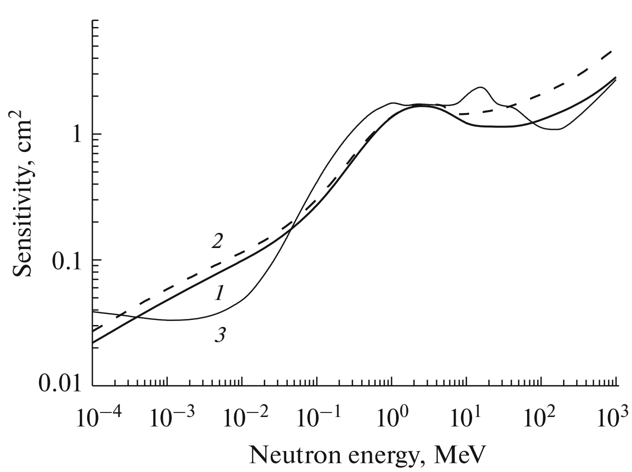


**Fig. 7.** SF of the dosimeter at different alignments of neutrons incident on it from above: (*1*) the case of lateral irradiation, (*2*) the case of dosimeter edge irradiation from above, and (*3*) function $h^*(10, E)$ (normalization at 2 MeV) [6].

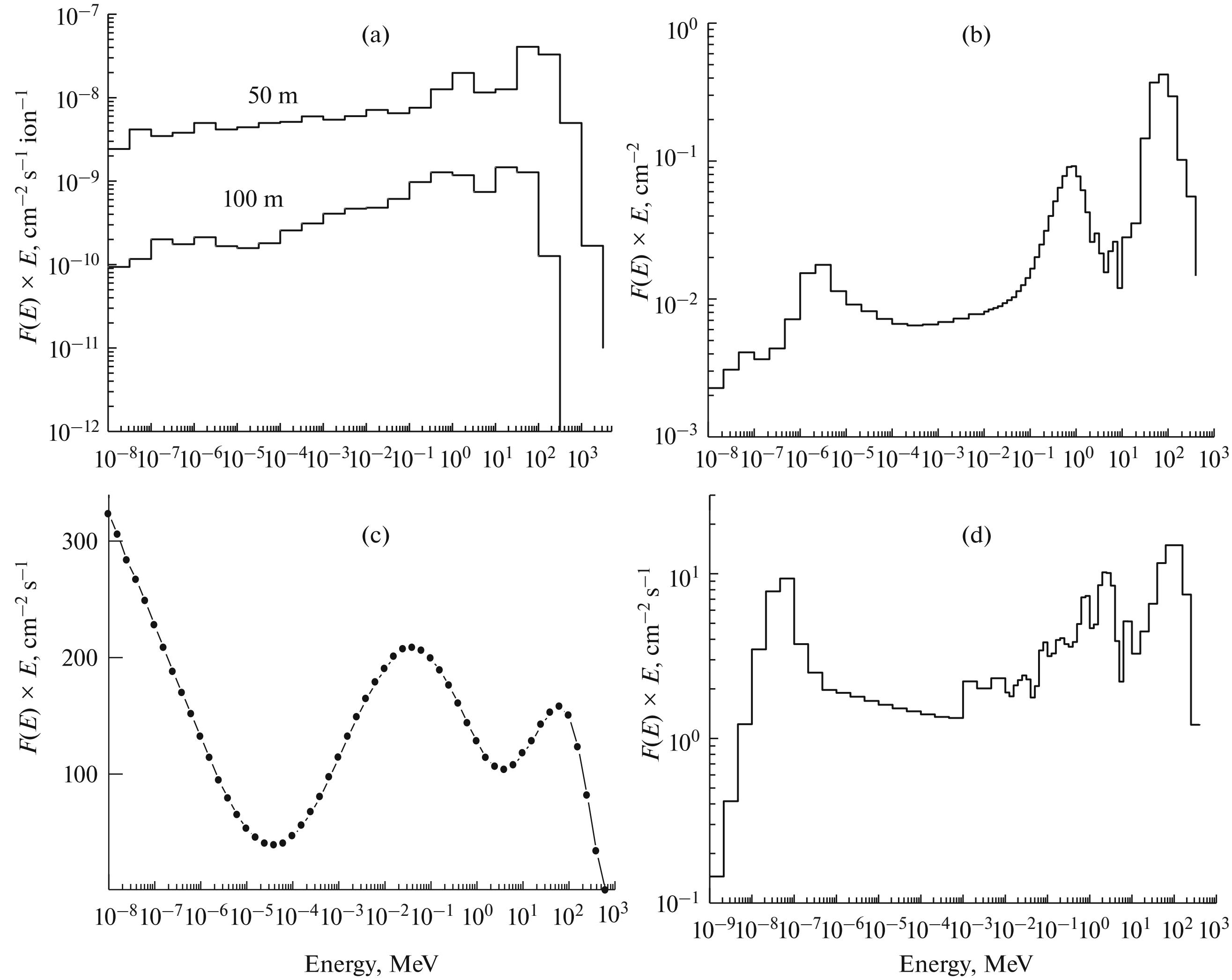


**Fig. 8.** Spectra of neutrons used for dosimeter testing. (a) Skyshine neutron spectrums at distances of 50 and 100 m from the center of the JINR Nuclotron calculated using GEANT4 software [8], (b) spectrum of neutrons at the KEK synchrotron (location 11) [14], (c) spectrum of neutrons of reference field over the JINR phasotron containment [13], and (d) spectrum of neutrons in reference basic floor{field} CERN [14].

## 3. MATHEMATICAL VERIFICATION OF THE ADEQUACY OF DOSIMETER READINGS IN THE FIELDS OF SCATTERED RADIATION FORMED AROUND HIGH-ENERGY ACCELERATORS

Calculation experiments based on the known high-energy skyshine neutron spectra [8], the spectrum of reference field neutrons at the JINR synchrocyclotron [13], the spectrum of neutrons of the Concrete, the side reference field (CERN) [14], and the spectrum obtained at 12 GeV KEK synchrotron [14] were carried out to test the dosimeter. Thereto, the ambient neutron doses counted according to the dosimeter SF for the specified spectra (the "measured" doses) were compared with the ambient neutron doses obtained by a convolution of spectra with dependence $h^*(10, E)$ under conditions of lateral irradiation (the "true" doses). The neutron spectra are presented in Fig. 8.

The results of tests are presented in Table 1, where the ambient dose of neutrons obtained by convolution of the spectrum with $h^*(10, E)$ is designated as H*(10) and the ambient dose obtained with the dosimeter SF is designated as $H^*(10)_d$.

Apparently, the dosimeter readings in these neutron fields differ from the values of neutron ambient dose H*(10) by no more than 30%, which completely meets the requirements for the measuring accuracy of the operative and zonal radiation control. Thus, the proposed dosimeter displays some benefits in comparison with commercially available foreign analogs and can be applied to measure ambient doses and for mon-

**Table 1.** Comparison of ambient doses measured by the dosimeter and true values of ambient doses for the neutron spectra presented above upon the lateral irradiation of the dosimeter by neutrons

| No. | Neutron spectrum | $H^*(10)_d$, pSv | $H^*(10)$, pSv | $H^*(10)/H^*(10)_d$ |
|---|---|---|---|---|
| 1 | A, skyshine spectrum, 50 m | $8.6 \times 10^{-17}$ | $1.1 \times 10^{-16}$ | 1.3 |
| 2 | A, skyshine spectrum, 100 m | $3.8 \times 10^{-18}$ | $5.3 \times 10^{-18}$ | 1.3 |
| 3 | B, KEK synchrotron 12 GeV | $6.7 \times 10^{-10}$ | $8.0 \times 10^{-10}$ | 1.2 |
| 4 | C, synchrocyclotron reference field, JINR | $3.0 \times 10^{-10}$ | $3.7 \times 10^{-10}$ | 1.2 |
| 5 | D, reference field, CERN | $5.2 \times 10^{-10}$ | $6.30 \times 10^{-10}$ | 1.3 |

itoring the radiation situation in neutron fields at high-energy accelerators.

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