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^{3}He-DETECTORS IN EXPERIMENTS AT THE POWERFUL PULSED ACCELERATORS

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1. Introduction

The use of thermal neutron detectors (TND) [1-3] for measuring characteristics of nuclear reactions with creation of neutrons in experiments at powerful pulsed accelerators is becoming important. Considering special features of powerful accelerators (current and load voltage of ~ MA and ~ MV, respectively; powerful bremsstrahlung in the photon energy region $0 \div 600$ KeV, preceding or accompanying the process of acceleration; electromagnetic noise) [4-8], neutron detectors and their related read-out electronics should be modified as compared with the design for traditional use.

The present paper is dedicated to measurement of the characteristics of the ^{3}He - based thermal neutron detectors developed by us for studying of nuclear reactions at ultralow energies of collision particles at pulsed plasma accelerators [4-8].

2. The detector design

The neutron detector is schematically shown in Fig.1. The detector consists of two sections, each comprising 5 counters filled with mixture $^3He+Ar+CO_2$ at a pressure of 4 atm (The partial pressure of ^{3}He, Ar and CO_2 is 2, 2 and 0.03 atm respectively). The counters are 30 mm in diameter and 500 mm long. The diameter of the central thread is 20 μm. The counters are enclosed a polyethylene moderator, whose basic thickness is 91 mm. The body of the detector measures (640x296x95 mm) and is made of an aluminum sheet by of 1.5 mm thick. The body of the detector carries special mounts for additional moderator layers. In what follows, by the thickness of the front and back layers (in the direction of the incident neutron flux) is meant the thickness of the corresponding additional moderator layers.

The outputs of all ten ^{3}He counters are connected in parallel to the charge preamplifier placed inside the body of the detector. This body in turn is a rather good screen against powerful electromagnetic noise.

3. Detector characteristics

a. Neutron recording efficiency

One of the basic characteristics of the TND is its neutron recording efficiency. It is known that the recording efficiency is essentialy dependent both on the energy spectrum of neutrons, hitting the TND and on his moderator thickness. Therefore, we found the optimum thickness of both the front and the back layers of the TND moderator and the corresponding efficiency for a quite wide neutron range. The experiments were carried out with ^{252}Cf and Pu + Be neutron sources (experimental setup 1, see Fig. 2a) and with a monoenergetic neutron beam from the reaction $d + t \rightarrow {}^{4}He + n$ (E_n=14,1 Mev) of the electrostatic generator /9/ (experimental setup 2, see Fig. 2b).

The formula for calculation of neutron recording efficiency for setup 1 is

$$\varepsilon_n = \frac{N_n^{reg} - N_{backg}^{reg}}{I_n \Omega_n t} , \qquad (1)$$

where N_n^{reg} is total number of neutrons registered by the detector for the time T of its irradiation it by the neutron flux from the ^{252} Cf (Pu-Be) source; N_{backg}^{reg} is the number of the recorded background events (neutrons, scattered from the floor and the walls of the experimental hall and recorded by the detector); Ω_n is the solid angle of the detector; I_n is the intensity of the neutron flux emitted by the source in the solid angle 4π. The value N_{backg}^{reg} was determined in additional experiments (see Fig. 2a) with the a moderator 2 placed in the middle of the distance between the source and the detector. The thickness of the moderator along the neutron flux is approximately 460 mm. With this moderator, only neutrons scattered from the walls, the floor and the ceiling of experimental hall hit the detector (the chosen thickness of the moderator was 4 times larger than the fast neutron flux half-attenuation thickness of polyethylene).

The neutron energy spectra measured with the ^{252}Cf and Pu + Be sources [10,11], are presented in Fig. 3. (The neutron spectrometric channel consists of an amplifier and the ADC).

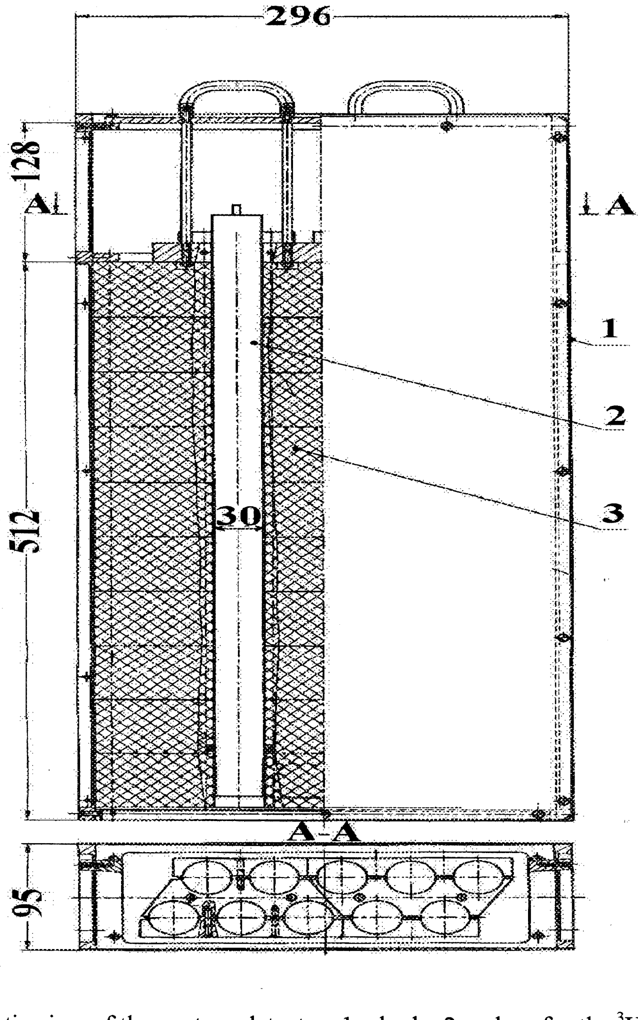

Fig. 1. Schematic view of the neutron detector: 1 – body, 2 – place for the ^{3}He detector, 3 – polyethylene moderator

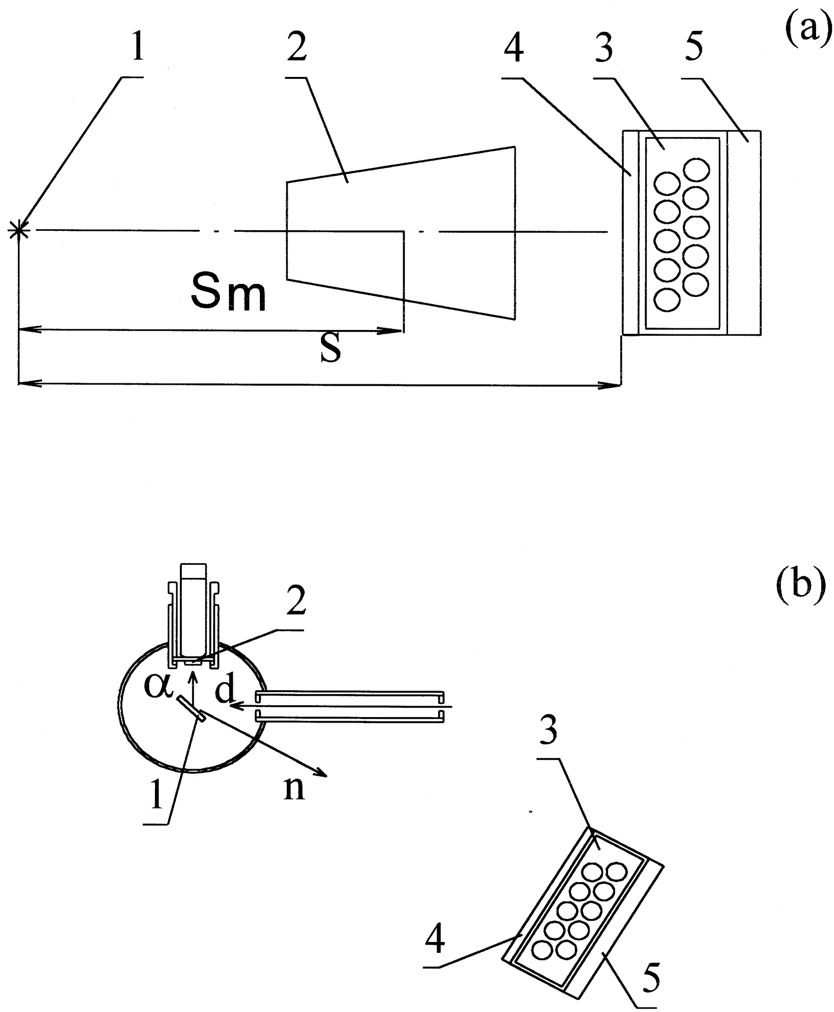

Fig. 2. a) – Experimental setup with the ^{252}Cf, Pu + Be sources: 1 – ^{252}Cf (Pu + Be) neutron source; 2 – polyethylene moderator; 3 – ^{3}He-detector; 4,5 – front and back walls of the detector

b) – Experimental setup at the Van de Graaf electrostatic generator : 1 – tritium target; 2 – α -detector, 3 – ^{3}He-detector; 4,5 – front and back walls of the detector.

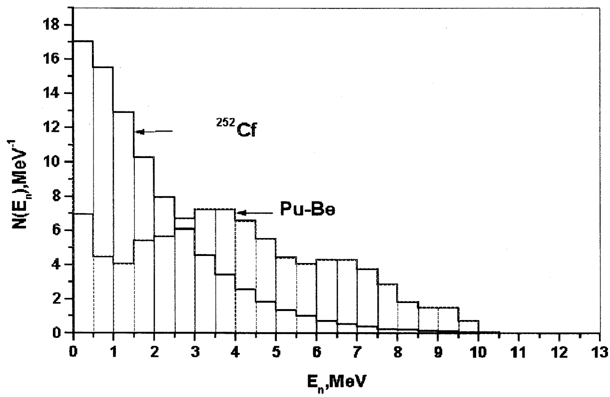

Fig. 3. Energy spectra of neutrons from the ^{252}Cf and Pu + Be sources.

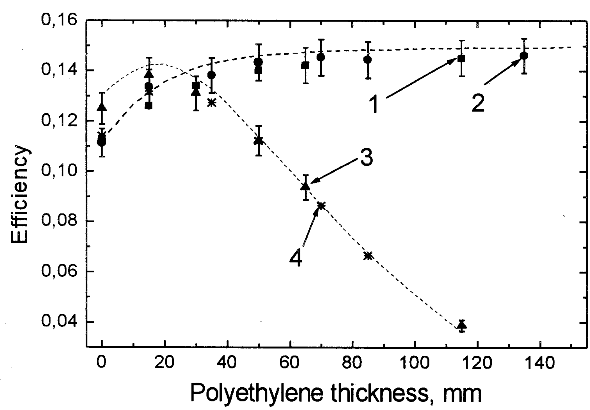

Fig. 4. Dependence of the recording efficiency for neutrons emitted from the ^{252}Cf source on the thickness of the front and back layers of the polyethylene moderator arranged perpendicularly to the direction of the neutron flux incident on the ^{3}He detector: 1 and 2 – front layer of 35 and 15 mm; 3 and 4 – back layer of 35 and 15 mm. Dotted lines are the Monte-Carlo calculations corresponding to measuring conditions, 2 and 3.

By way of example, Fig.4 and 5 show the dependence of the intrinsic neutron recording efficiency on the thickness of the front and back walls of the ^{3}He - detector moderator for the ^{252}Cf and Pu + Be neutron sources at S = 2 m. As is evident from the figures, the optimum thickness of the front and back polyethylene walls of the detector are 15 mm and 50 mm for the ^{252}Cf neutron source and 35 and 50 mm for the Pu + Be source. The dotted lines in these figures show this dependence calculated by the Monte-Carlo method (MC) with the program MCNP [12].

Good agreement of the experimental and computational results is observed. Note that the optimum thickness of the front and back walls of the ^{3}He detector moderator in the direction of the incident neutron flux; the contribution from background neutrons scattered from the walls and the floor of the hall to the total number of recorded neutrons was determined for correct measurement of the intrinsic efficiency of the detector in relation to recording of neutrons for each fixed distance between the neutron source and the detector (see Fig. 6 and 7, the relationsships calculated by the Monte-Carlo method are shown by the dotted lines).

Figure 8 displays the measured recording efficiency for neutrons emitted by the ^{252}Cf source at different distances from the detector. During the measurements the effective thickness of the moderator does not significantly varies with the distance between the neutron source and the detector. This constancy (see Fig. 8) is due to absence of the systematic errors in the measurements. The figure also displays the recording efficiencies calculated by the Monte-Carlo method. The calculations and the experiment are seen to be in good agreement, which in turn confirms correctness of the algorithm for the analysis of the experimental data.

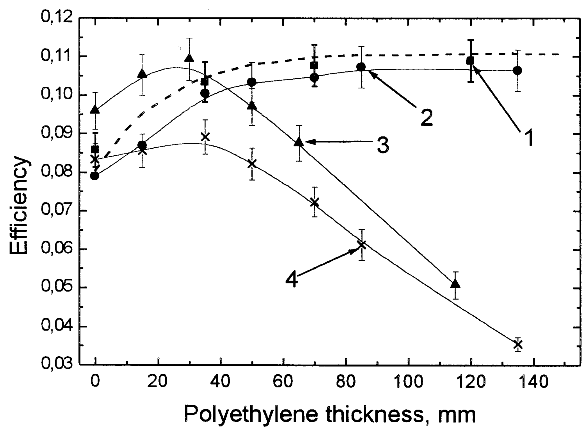

Fig. 5. Dependence of the "intrinsic" recording efficiency for neutrons emitted from the Pu-Be source on the thickness of the front and back layers of the polyethylene moderator arranged perpendicularly to the direction of the neutron flux incident on the ^{3}He detector: 1 and 2 – front layer of 35 and 15 mm; 3 and 4 – back layer of 35 and 15 mm. Dotted lines are the Monte Carlo calculations corresponding to measuring conditions 1. The solid lines are the results of approximating the experimental data under c conditions 2,3,4.

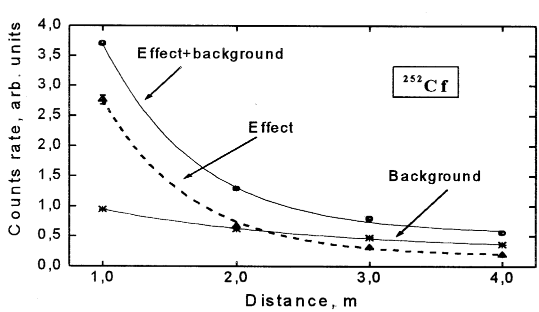

Fig. 6. Dependence of the intensity of the recorded events on the distance between the ^{252}Cf source and the detector. The dotted line is the Monte-Carlo calculation.

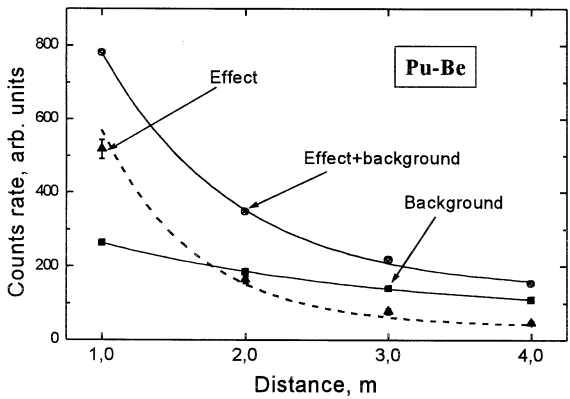

Fig. 7. Dependence of the intensity of the recorded events on the distance between the Pu-Be source and the detector. The dotted line is the Monte-Carlo calculation. The solid lines are the result of experimental data approximation.

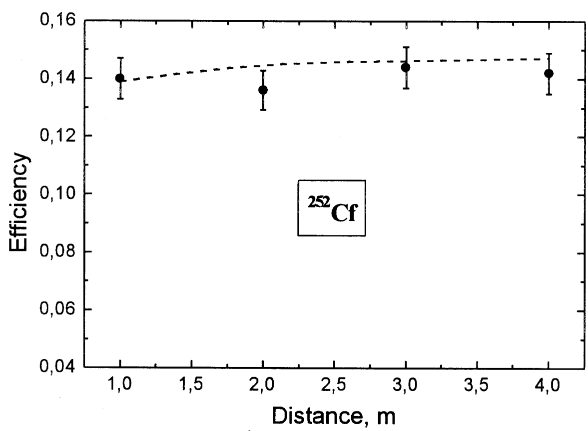

Fig. 8. Dependence of the intrinsic neutron recording efficiency on the distance between the ^{252}Cf source and the detector. The dotted line is the calculation.

In the case of experimental set up 2 the total neutron flux $I_n\ \Omega_n$ produced in the dt-reaction was defined as

$$I_n = \frac{N_\alpha^{reg} \int\limits_{\Omega_n} \frac{d\sigma_{dt}^{n}(\Theta)}{d\Omega_n} d\Omega_n}{\Omega_n \varepsilon_\alpha T \int\limits_{\Omega_\alpha} \frac{d\sigma_{dt}^{\alpha}(\Theta)}{d\Omega_\alpha} d\Omega_\alpha}, \qquad (2)$$

where N_α^{reg} is the number of α-particles recorded for the time T ; Ω_n, Ω_α are the solid angles of the neutron and α-detectors; ε_α is the α-particle recording efficiency; $d\sigma_{dt}^{n}(\Theta)/\Omega_n$, $d\sigma_{dt}^{\alpha}(\Theta)/d\Omega_\alpha$ are the angular distributions of neutrons and α-fragments produced in the dt-reaction. The α-particle recording efficiency for this experimental setup is ~ 1 and the relative solid angle of the α-detector is $9 \cdot 10^{-4}$. The neutron recording efficiency was found by formula (1) with I_n calculated by formula (2).

The efficiency ε_n was measured at the deuteron beam energy 450 keV. Titanium tritide (TiT_2). was used as a tritium target. The neutron detector was placed at the angle 150° with respect to the direction of the incident deuteron beam. Apart from the TiT_2 target, the α - particle detector and the current integrator for measurement of intensity of the deuteron beam incident on the tritium target were placed in the measuring chamber. According to the dt-reaction kinematics, the energy of neutrons emitted from the target at the angle 150° (with respect to the direction of the deuteron beam) and incident on the detector is 13 MeV.

The α-detector was a disc-shaped plastic scintillator 10 mm in diameter and 0.5 mm thick, placed 75 mm away from the center of the tritium target at the angle of 90° with respect to the direction of the deuteron beam incident on the target. To prevent scattered deuterons from hitting the α-detector it was covered with an aluminium foil 6.3 μm thick.

It is necessary to note, that in parallel with the above measurement of $I_n\ \Omega_n$ the neutron yields measured in each exposure were normalized to the total deuteron flux on the tritium target. This procedure allowed the relation between neutron recording

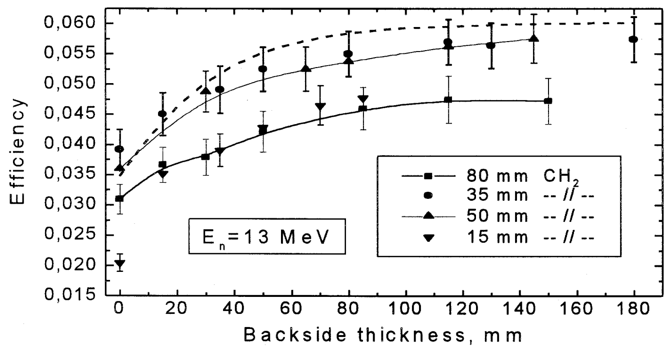

Fig. 9. Dependence of the intrinsic recording efficiency for neutrons from the dt – reaction on the thickness of the back wall of the polyethylene moderator for different thickness of the front polyethylene wall. The dotted line is the calculation corresponding to the front wall thickness 35 mm. The solid lines is the result of the experimental data approximation corresponding to the thickness of the front wall 50 and 80 mm.

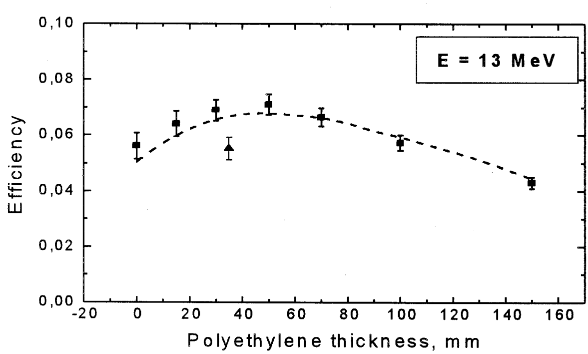

Fig. 10. Dependence of the intrinsic recording efficiency for neutrons with energy 13 MeV on the thickness of the front polyethylene wall when the back wall of the detector is a Pb layer 50 mm thick. ▲ are the efficiency values for the front and back polyethylene wall 35 and 50 mm thick. The dotted line is the calculation.

efficiencies in each exposure to be independently determined and compared with the similar relations found with the absolute value I_n. Figure 9 displays dependence of the recording efficiency for neutrons with energy 13 MeV on the thickness of the back polyethylene wall of the detector for the front wall thicknesses 15, 35, 50 and 80 mm. The dotted line is the relation calculated by the Monte-Carlo method. As is seen, the optimum thickness of the front and back polyethylene walls for monoenergetic neutrons with energy 13 MeV is 35 mm and 60 mm respectively. Thus the intrinsic neutron recording efficiency is ~ 5.5%. Note that the use of a 50-mm-thick Pb layer for the back wall instead of a polyethylene layer of the same thickness results in an increase of 20 % in the recording efficiency (see Fig. 10). This increase is due to an increase in the albedo of epithermal neutrons after replacement of the polyethylene back wall of the detector by a Pb wall. No such increase in the recording efficiency was found in measurements with the ^{252}Cf and Pu + Be sources. This is because the fraction of epithermalized neutrons reaching the back layer of the absorber is larger the higher the initial energy of neutrons incident on the TND. Therefore, in the case of using a source of monoenergetic neutrons with energy 13 MeV the fraction of nonthermalized neutrons incident on the back layer of the absorber and undergoing back-scattering is considerably larger than in the case of using the ^{252}Cf and Pu-Be sources (see Fig. 3).

Apart from carrying out measurements, we investigated the effect of the passive Pb shielding in front of the detector on the neutron recording efficiency. This investigations, as was pointed out in the Introduction, were dictated by particular conditions of using thermal neutron detectors in experiments at high-current ionic pulsed accelerators with a Z-pinch [1-3]. [1]

According to the results of [12-13], a lead shield ~50 mm thick is necessary to "suppress" the background loading of the TND .

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[1] At working on this type accelerators it is need supress the loading of the TND by bremsstrahlung and X-radiation up to enough level. As a rule the passive Pb shielding is used for that.

Figure 11 displays the dependence of the intrinsic recording efficiency for monoenergetic neutrons with energy 13 MeV and neutrons from the ^{252}Cf and Pu + Be sources on the lead layer thickness in front of the detector. It should be mentioned that thickness of the polyethylene moderator in each concrete case corresponded to the optimal values and were selected by the procedure described above. The recording efficiency was determined by formulas (1) and (2), where $I_n\ \Omega_n$ was the intensity of the neutron flux incident on the lead layer covering the frontal plane of the neutron detector and Ω_n was the solid angle determined by the Pb layer.

As is evident from Fig.11, when the ^{252}Cf and Pu + Be sources are used and the back Pb layer is 50 mm thick the recording efficiency for neutrons incident on the frontal part of the detector decreases by 35% and 20% respectively. The figure also displays the results of Monte-Carlo calculations. Good agreement between the calculations and the experiment is seen.

As to monoenergetic neutrons with energy 13 MeV, the inverse effect is observed: the neutron recording efficiency ε_n increases as the forward Pb layers thickness increases in the range 0 ÷ 50 mm. This increase in the efficiency is due to possible formation of neutrons in Pb (n, 2n), Pb (n, 3n) reactions. With the Pb layer 50 mm thick, the neutron recording efficiency increases by ~ 20%.

b. Lifetime of neutrons in the detector

The knowledge of the effective neutron lifetime in the moderator of the ^{3}He detector is necessary for correct determination of the neutron yield from the reaction under study. The lifetime of a neutron in the detector is defined as a time interval from the instant of a fast neutron hitting the detector to the instant of its being captured by the ^{3}He nucleus (the instant when a ^{3}He counter signal appears) or by the proton ($p + n \rightarrow D + \gamma$ (2.3 MeV)). This time interval comprises the neutron thermalization time in polyethylene and the neutron diffusion time in the moderator till it is captured by the ^{3}He-counter or by hydrogen in polyethylene. The neutron lifetime distribution (the thermalization time is considerably shorter than its diffusion time in the moderator)

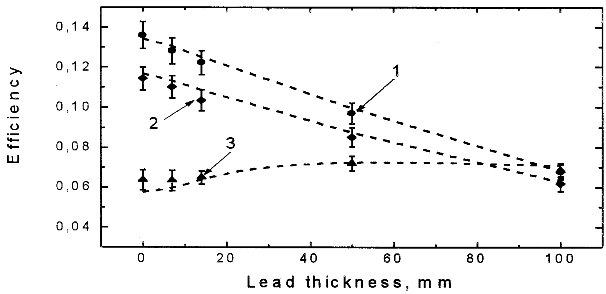

Fig. 11. Dependence of the intrinsic neutron recording efficiency on the thickness of the lead layer in front of the detector for different neutron sources: 1 – ^{252}Cf (the front and back polyethylene layers are 15 and 50 mm thick respectively); 2 – Pu-Be (front layer 35 mm, back layer 50 mm); 3 – E_n = 13 MeV (front layer 35 mm, back layer 70 mm). Dotted lines are the calculations.

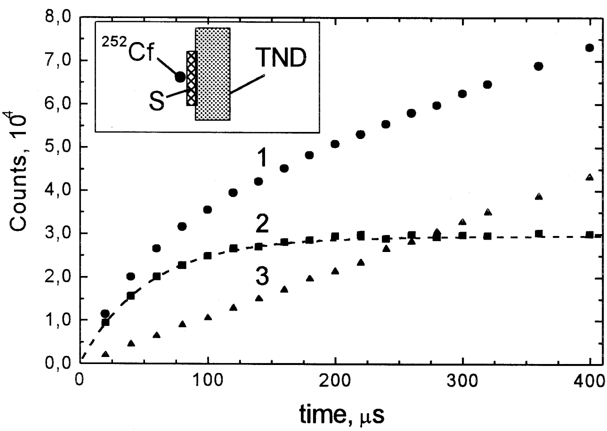

Fig.12. The total counting of events N_n^{reg} (t) registered in the working (1) and backgroud (3) exposures and their corresponding differences obtained with the ^{252}Cf neutron source. The dotted lines are the calculations.

can be represented as exponent with the index equal to the so-called effective neutron life in the detector. Naturally, to each particular energy distribution of the neutrons hitting the detector will correspond a particular effective neutron lifetime in it.

The time distribution of the detector output signals dN_n^{reg} /dt, the intensity of the neutron flux from the reaction under study *In* and the reaction cross section σ_n can be defined as [2]

$$dN_n^{reg} / dt = \frac{I_n \Omega_n \varepsilon_n \Delta T}{\tau_n} \exp(-t/\tau_n) \ , \tag{3}$$

$$I_n = \frac{N_n^{reg}}{\Omega_n \varepsilon_n \Delta T}, \qquad \sigma_n = \frac{I_n}{I_p dn} = \frac{N_n^{reg}}{\Omega_n \varepsilon_n \Delta T I_p dn}, \tag{4}$$

where ΔT is the neutron pulse duration; N_n^{reg} is the number of the registered neutrons; I_p is the flux of particles incident on the target and inducing the nuclear reaction under study; d is the target thickness, n is the target nuclear density. To confirm what was said above, we consider as an example the study of dd - reaction d+d → He + n (2.5 MeV) with using a plasma pulsed accelerator [1-3]. The time distribution of the TND output signal is described with a rather good accuracy by formula (3) since the duration of a neutron pulse determined by the duration of a high-voltage pulse (t_{HV}=60-80ns) is considerably shorter than the neutron lifetime in the ^{3}He detector (tens of microseconds). Approximating the time distribution of the registered neutrons from the dd-reaction by (3) and using (4) with the known Ω_n, ε_n and τ_n we easily find the absolute neutron yield and the cross section of the reaction under study.

For the dd-reaction in question τ_n can be measured at the pulsed neutron generator by using the same reaction as the source of neutrons with the energy 2.5 MeV. In the general case, when there is an energy distribution of neutrons produced in the reactions under study, τ_n is found by Monte Carlo calculations. However, to check the algorithm

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[2] In experiments at pulsed accelerators the pulse repetition rate should meet the condition $f \ll 1/\tau_n$, if the pulse duration considerably shorter than the neutron lifetime in the detector.

of the τ_n calculation program, the calculated and experimental τ_n values should be compared. The experimental values can be obtained by using radioactive ^{252}Cf, Pu –Be (Po-Be) sources.

Below the procedure of measuring τ_n with the ^{252}Cf and Pu-Be (Po-Be) sources is briefly described. Figure 12 (insertion) displays the experimental setup. Between the neutron source and the TND there is a plastic scintillator detector S of fast neutrons (100x100x10 mm). The front and back layers of the polyethylene moderator were optimally thick for the ^{252}Cf and Pu-Be sources (see part 3a). Let us follow the fate of the neutrons emitted by the source in the solid angle of the scintillator of the detector S in the given geometry . Owing to elastic neutron scattering on protons of the scintillator the neutrons can be recorded by the detector S with the probability W ~ 1 - exp (-nσl), where n is the density of hydrogen nuclei in the scintillator, σ is the cross-section of elastic neutron scattering on protons which is a function of the neutron energy, S is the scintillator thickness along the pathway of the incident neutron (at the neutron energy below 15 MeV the energy distributions of the of recoil protons in the center-of-mass system is isotropic).

Neutrons scattered in the scintillator in the forward hemisphere hit the TND, where they are moderated with the possible subsequent capture by nuclei ^{3}He (n + ^{3}He → T + p), or protons (n + p → D + γ) (2.23 MeV). The instant when the scintillation detector S signal appears is the lifetime origin for neutrons in the TND (physical zero time). Thus, we can measure the distribution of time intervals $t = t_{TND} + t_s$ (where t_{TND} and t_s are the instants when the signals from the TND and scintillation detector S appear) and the numbers of events $dN_n^{reg}(t)$ registered by the TND during different time intervals t.

For this algorithm of τ_n measurement the analytical expressions describing the distribution of time intervals t and the dependence N_n^{reg} (t) per detector S operation event have the form :

$$dN_n^{reg}(t)\ /dt = \frac{A}{\tau}\ \exp\left(-t/\tau_n\right), \qquad A = N_n\,\varepsilon_n\ , \tag{5}$$

$$\Delta N_n^{reg}(t) = A\,(1 - \exp(-t/\tau_n)), \qquad (6)$$

where $\Delta N_n^{reg}(t)$ is the number of events recorded by the TND during the interval of duration t beginning with zero; N_n is the number of neutrons incident on the TND after operation of the detector S.[3]

Note that operation of the detector S can be due to recording of not only fast neutrons but also γ-radiation accompanying both fission of the ^{252}Cf nuclei and the reaction $\alpha + {}^{9}Be = {}^{13}C^{*} = {}^{12}C + n + 5.71$ MeV proceeding in the Pu-Be source.

In the given experimental setup τ_n is measured correctly if the intensity of the neutron flux incident on the detector $(I_n\,\Omega_n)$ meets the condition $(I_n\,\Omega_n\,\varepsilon_n) << 1/\tau_n$. The given condition arises from the necessity to reduce as much as possible the probability of recording events belonging to two and more successive acts of ^{252}Cf fission or of the reaction $^{9}Be(\alpha, n)\,^{12}C$

Figure 12 displays both the total counts $N_n^{reg}(t)$ of events registered in working and backgrownd exposures for the ^{252}Cf and Pu-Be neutron sources and the corresponding differences of those values. Approximation of the experimental dependence $N_n^{reg}(t)$ by expression (6) yielded the lifetime of neutrons τ_n in the detector of thermal neutrons in the case of using the ^{252}Cf and Pu-Be sources:

$$\tau_n^{exp}(^{252}Cf) = (53.3 \pm 0.6)\ \mu s; \quad \tau_n^{exp}(\text{Pu-Be}) = (56.8 \pm 1.5)\ \mu s$$

The values of τ_n deduced by approximation of the calculated integral distributions $\Delta N(t)$ by expression (6) are

$$\tau_n^{MC}(^{252}Cf) = (53.6 \pm 0.5)\ \mu s; \quad \tau_n^{MC}(\text{Pu-Be}) = (55.2 \pm 0.9)\ \mu s$$

The calculated and experimental values of τ_n found for the ^{252}Cf and Pu-Be neutrons sources are seen to be in good agreement. The difference between the values $\tau_n(^{252}Cf)$ and τ_n (Pu-Be) is, as expected, due to different mean slowing-down times of the neutrons emitted by the ^{252}Cf and Pu-Be sources (see Fig. 3). Though the spectra of neutrons from the Pu-Be and ^{252}Cf sources are very different in shape, the difference in

[3] The mean neutron multiplicity k per ^{252}Cf fission event is 3.75.

values of τ_n is not so pronounced. This is because the mean time of neutron moderation in a polyethylene moderator (a few microseconds) is substantially smaller than the time of diffusion, which is the major contributor to τ_n.

It should be noted that in case of the ^{252}Cf source τ_n may be determined by measuring the distribution of the time intervals between the successively recorded events from one ^{252}Cf fission event.

The electronic logic developed by us allowed measuring the integral dependence of the event counting $N_n^{reg}(t)$ recorded by detector S and the TND with measurement time varying from 0 to 800 μs.

3. Conclusion

Our investigations have allowed us to determine the basic characteristics of the developed ^{3}He detectors. Apart from determination of the neutron recording efficiency in a wide energy range $E_n = 0 \div 13$ MeV, the lifetimes of neutrons in the detector and the optimum thicknesses of the polyethylene moderator of the detector and the Pb shelding layer suppressing the background of the detector to a negligible level in strong γ - quantum and bremsstrahlung fields are found. Comparison of the calculated and experimental lifetimes of neutrons from the ^{252}Cf and Pu-Be sources in the detector demonstrates that the algorithm of the program for calculation of this value in the neutron energy range 0-15 MeV is correct. This in turn allows calculation of τ_n for any form of the neutron energy distribution in the above energy range. The developed detectors can be successfully used in experimental investigations of fusion reactions of light nuclei at ultralow energies (~ keV) with the use of powerful pulsed ion accelerators based on acceleration of a liner plasma.

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^{3}He-детекторы в экспериментах
на мощных импульсных ускорителях

Рассмотрена возможность использования детектора тепловых нейтронов в сильных полях γ-квантов и тормозного излучения. Описывается конструкция детектора тепловых нейтронов на основе 10 пропорциональных счетчиков, заполненных ^{3}He под давлением 2 атм и помещенных в полиэтиленовый замедлитель. Приведены результаты измерения эффективности регистрации нейтронов и времени их жизни в созданном детекторе при облучении его потоками нейтронов из *dt*-реакции и от источников ^{252}Cf и Pu–Be. Экспериментальным путем проведена оптимизация толщин полиэтиленового замедлителя детектора и слоя Pb, используемого для подавления фоновой загрузки детектора при работе в полях мощного электромагнитного излучения.

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Перевод авторов

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^{3}He-Detectors in Experiments at the Powerful Pulsed Accelerators

A possibility of using a thermal neutron detector in the high γ-quantum and bremsstrahlung fields is considered. The design of the thermal neutron detector consisting of 10 counters filled with ^{3}He under the pressure of 2 atm and enclosed in the polyethylene moderator is described. The results of measuring the neutron recording efficiency and neutron lifetimes by this detector exposed to a neutron flux from the *dt*-reaction and from the ^{252}Cf- and Pu–Be-sources are reported. The thicknesses of the polyethylene moderator and the Pb-layer used for suppression of the background in the fields of powerful electromagnetic radiation are optimized.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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