84-735

объединенный
институт
ядерных
исследований
дубна

E1-84-735

V.M.Bystritsky, J.Wozniak, V.G.Zinov

CHARACTERISTICS OF THE LARGE-VOLUME NE-213 NEUTRON COUNTERS FOR MUON CATALYZED FUSION INVESTIGATION

Submitted to "Nuclear Instruments and Methods"

1984

1. INTRODUCTION

The great efforts were made in the past to investigate experimentally as well as by the Monte-Carlo simulation the neutron registration efficiency for the intermediate neutron energy range ($E_n \lesssim 15$ MeV) of a series of organic scintillators as NE-213, NE-102A, NE-211, Pilot B (refs. 1-10, see also review /11/). The investigations have been practically limited to the scintillators with a small active volume (~1 l). The evident advantages of the large-volume counter are connected with a significant increase of efficiency and a peak-type form of the recoil protons spectrum. Such a detector can be especially useful for registration of neutrons from rare processes and also in the case when the knowledge of the absolute value of efficiency ϵ is needed to make precise interpretation of the experimental data (the relative error of ϵ tends to be near zero when ϵ attains unity). This is the situation in the experimental investigations of the muon catalyzed fusion, where from analysis of the yields and time distributions of fusion neutrons one can obtain basic parameters of μ-atom and μ-molecular processes (see, e.g., ref. /12/). However, for a detailed investigation of the large-volume detectors feasibility the discussion of such problems as increasing of background, time resolution, lifetime of neutrons in the scintillator etc., is needed. When calculating the efficiency, it should be also explained to what extent the influence of the light attenuation in the scintillator should be taken into account. Surprisingly, treatments of this problem in several papers are extremely different.

The aim of this work is to determine by means of Monte-Carlo calculations the principal characteristics of the large-volume NE-213 counters (80-200 l) from the point of view of its application to registration of neutrons from fusion reactions, muon capture by protons:

$$d\mu + d \rightarrow dd\mu \rightarrow {}^3He + n + \mu^- \qquad (E_n = 2.5 \text{ MeV}) \qquad (1a)$$

$$\mu^- + p \rightarrow n + \nu_\mu \qquad (E_n = 5.2 \text{ MeV}) \qquad (1b)$$

$$t\mu + d \rightarrow dt\mu \rightarrow {}^4He + n + \mu \qquad (E_n = 14.1 \text{ MeV}) \qquad (1c)$$

$$t\mu + t \rightarrow tt\mu \rightarrow {}^4He + n + n + \mu^- + 11.3 \text{ MeV} \qquad (1d)$$

and similar processes which involve neutrons up to 15 MeV. The calculations are performed for real conditions of experiments on the muon channel of the JINR synchrocyclotron (Fig.1).

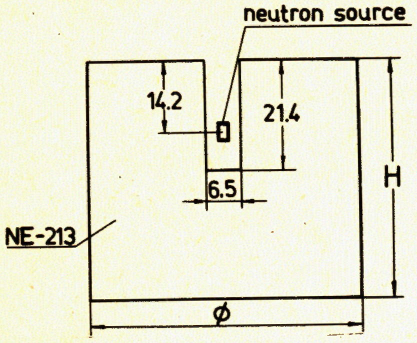

Fig.1. The sketch of the scintillator geometry.

The details of the calculation procedure as well as its verification are described below in Section 2. The importance of the light attenuation and the method of taking it into account are presented in Section 3. Section 4 contains the results of calculations of the efficiency and other characteristics of the detectors with the active volume of 84 and 200 l of the NE-213 scintillator.

2. MONTE-CARLO EVALUATION

Our program is similar to the majority of other Monte-Carlo codes used for description of the transport of neutrons in the scintillators and for calculation of their efficiency. It may be applied to any geometrical systems. The detailed description was given elsewhere [14,15] so only a summary including the major modifications is given here.

The source of neutrons was a cylindrical target [13] in which one of the reactions (1) takes place. A homogeneous space distribution of reaction vertices was assumed. For the case of $tt\mu$ reaction the pure phase-space kinematics was used to establish energy and angular distributions of primary neutrons. A part of calculations was performed for a point source of monoenergetic neutrons or for the neutron beam geometry. The neutrons entered the NE-213 scintillator after eventual interactions in the target material and experimental apparatus parts, e.g., detector walls, where elastic, inelastic scatterings and absorption were taken into account (no more than two consecutive collisions). To describe the neutron history in the scintillator the following reactions were considered:

a) $^{1}H(n,n)^{1}H$ - (n-p) elastic scattering;

b) $^{12}C(n,n)^{12}C$ - (n-C) elastic scattering;

c) $^{12}C(n,n'\gamma)^{12}C$ - (n-C) inelastic scattering with the threshold 4.80 MeV;

d) $^{12}C(n,\alpha)^{9}Be$ - absorption (threshold 6.18 MeV);

e) $^{12}C(n,n')\,^{12}C^{*}(3\alpha)$ and $^{12}C(n,\alpha)^{9}Be^{*}(n')^{8}Be(2\alpha)$- inelastic scattering with production of three alpha particles. This list of reactions permits us to calculate the efficiency of neutron registration up to 15 MeV. The total and differential cross sections were compiled and tabulated from refs. [16-18]. The actual values were determined by proper interpolation. The anisotropy of neutron scattering in the c.m. system has been assumed excluding n-p elastic scattering and (d) reaction case. The two last reactions (e), which became appreciable only for neutrons with energy greater than 10 MeV, were treated approximately. In both cases the final state was described using four body phase-space kinematics.

The history of a neutron in NE-213 is followed until it either leaks out of the system (the backscattering in the detector walls is taken into account), or is absorbed or falls below a cut-off energy E_{lim}. For each neutron collision the light produced by a recoil particle is obtained using interpolation of the light-output data from ref. [8]. The edge effects were also considered for protons, using their ranges in NE-213. After taking into account the effect of light attenuation (if necessary, see next section) and energy resolution of the detector (in the same way as in refs. [14,15]) the light produced in the scintillator is summarized over neutron history to obtain a pulse-height spectrum. The storing of the characteristic times during neutron history allowed one to obtain different time distributions.

On the same base the program version for γ-ray transport through the scintillator and calculating the spectra of Compton electrons in the scintillator was made. Typical effects as Compton scattering, photoelectric absorption, and pair creation were included. The last version of the program was used to simulate the detector calibration by γ-ray sources.

In order to check the code the efficiency measurements for Drosg [8] and Thornton and Smith [9] cases were simulated by our Monte-Carlo technique. The detectors were small cylindrical NE-213 scintillators of dimensions: ϕ = 12 cm, h = 5.7 cm and ϕ = 12.7 cm and h = 3.8 cm, respectively. The comparison of measured and calculated efficiencies for different neutron energies and registration thresholds are shown in Figs.2 and 3. Excellent agreement is obtained.

3. LIGHT ATTENUATION IN THE SCINTILLATOR

There are different approaches to this question. A part of authors omit completely this problem and despite this obtain good agreement of calculated efficiencies with the experimental values [7,9]. Others try to take into account the fact of light attenuation by the scintillator itself finding this problem substantially significant [5,6].

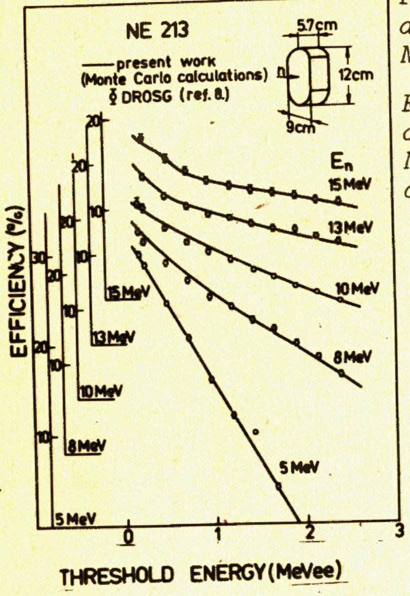

Fig.2. Comparison of measured [8] and calculated efficiency for NE-213 scintillator.

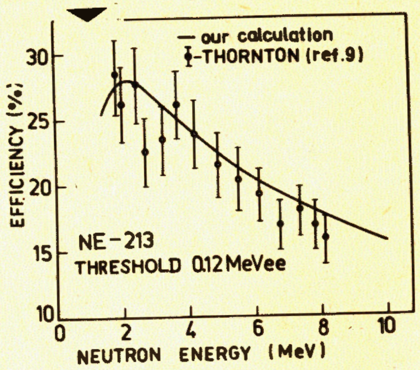

Fig.3. Comparison of measured [9] and calculated efficiency. Cylindrical NE-213 scintillator of dimensions: diameter - 12.7 cm, height - 3.8 cm.

As will be shown later, the exact calculation of such attenuation is not necessary if the energy scale of the detector is calibrated using the well known γ-ray sources.

It is evident that the change of the detector response arising from the light attenuation increases with the size of the scintillator. This can be seen from experiments of refs. [19] and [20] where a strong decrease of the high-energy spectrum edge was observed when scintillations were produced far away from the photocathode (~10 cm) in comparison with the case when they were produced near the photocathode. A precise evaluation of such attenuation by means of the Monte-Carlo method is extremely difficult due to complexity of light collection processes in the scintillator (multiple scattering and reflections of light). At the same time the poor accuracy of some parameters as reflection coefficient at the detector walls and linear coefficient of light absorption, which are necessary in the calculations, makes the results doubtful*.

The situation becomes better when γ-calibration is used. So, the spectrum of Compton electrons is distorted by attenuation of light in the same manner as the spectrum of recoil protons. A small difference may arise from different spatial distributions of light sources when using γ-rays or neutrons. In the consequence the detection threshold determined from γ-calibration does not correspond to the value which should be used in calculations of the neutron registration efficiency from recoil protons spectrum. Let us assume that the value of the detection threshold is adjusted to a known energy E^e of the highest energy Compton electrons when the γ-ray source is used ($E^{\gamma}_{thr} = E^e$). Since only a part of light produced by these electrons reaches the photocathode, the effective threshold would be $(A'_e/A_e)E^e$, where A'_e and A_e are the light outputs for electrons with and without attenuation effects taken into account, respectively. The energy of neutrons E^n should obey the condition $(A'_p/A_p)E^n = (A'_e/A_e)E^e$ to obtain the same effective threshold for recoil protons (A'_p and A_p for recoil protons have the similar meaning as A'_e and A_e). From this follows immediately that the threshold energy of neutrons (in equivalent electron-energy light units) is

$$E^n_{thr} = kE^{\gamma}_{thr}, \qquad (2)$$

where $k = \dfrac{A'_e/A_e}{A'_p/A_p}$.

Thus, the knowledge of the k-coefficient allows one to determine the efficiency of neutron registration on the basis of recoil protons spectra calculated for a transparent scintillator, using the value of the threshold corrected according to formula (2). Moreover, as $k \approx 1$, neglecting of the light attenuation in the calculations of efficiency is justified, especially for the low detector thresholds, nevertheless the arising error should be known.

In order to estimate this error for the case of a large-volume detector the calculations of the spectra and the efficiencies were performed for different neutron energies and registration thresholds. The both cases, one for the transparent scintillator and the other with the light attenuation included were considered. The detector was the cylindrical NE-213 scintillator with diameter 30 cm and height 30 cm. A point source of γ-rays or neutrons was placed in the middle of the face side of the scintillator and light produced in the scintillator was collected at the opposite side. The spectra of Compton electrons as well as the spectra of recoil protons were calculated in the energy ranges of 0.66-4.43 MeV and 2.5-14.1 MeV, respectively, then from the high-energy edges the A_e, A'_e, A_p, A'_p values were determined for gammas and neutrons. Since only the relative effect of light attenuation is of importance, an approximate model was adopted to describe this attenuation. We used the modified formula of Clark [6] for the fraction of light

*For example, the Nuclear Enterprises give a value 1/200 cm^{-1} of the coefficient of light absorption in NE-213 whereas from experiments of Kuijper et al. [19] this value is 1/150 cm^{-1}; in another work [4] a value 1/6 cm^{-1} is used in calculations (!)

produced in the i -th collision, reaching the photocathode:

$$f_i = \omega_i e^{-a\ell_i} + (1 - \omega_i) r e^{-a(2h-\ell_i)}, \qquad (3)$$

where: ω_i is fraction of the total solid angle subtended by the photocathode to the scintillation point; $a = 1/150\ \mathrm{cm}^{-1}$ is the linear light absorption coefficient for NE-213 (taken from ref. [19]); ℓ_i is the distance between the photocathode and the scintillation point; r is the reflection coefficient at the scintillator walls (assumed to be equal to unity).

The resultant value of the k-coefficient, being constant through the whole γ-ray and neutron energy ranges was calculated as $k = 0.97 \pm 0.01$. Figure 4 shows the calculated efficiencies of the described detector and the relative efficiency error $\frac{\Delta\epsilon}{\epsilon} = \frac{\epsilon(E^n_{thr}) - \epsilon(E^{\gamma}_{thr})}{\epsilon(E^n_{thr})}$ due to the neglecting light attenuation versus the relative threshold. As can be seen, even for so large scintillator the influence of light absorption is small and may be neglected if the detection threshold is sufficiently low.

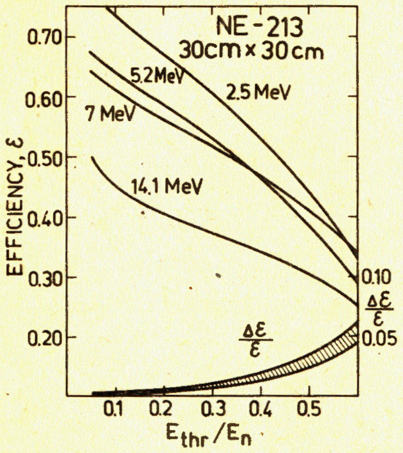

Fig.4. Efficiency of NE-213 scintillator (30 cm diam. and 30 cm height) for different neutron energy vs relative threshold (upper curves) and relative error which arise when neglecting the light attenuation effects (lower curve).

We tested also the above described procedure calculating the efficiency of the long NE-213 scintillator ($100 \times 11.5 \times 5.6\ \mathrm{cm}^3$) for which the attenuation of light changes substantially the recoil protons spectrum. The experimental data of Netter et al. [10] and calculated efficiencies are compared in Table 1 for 2 MeV and 7 MeV neutron beams incoming the centre of the detector and for the 0.75 MeV threshold. Good agreement is obtained.

4. EFFICIENCY AND TIME CHARACTERISTICS OF LARGE-VOLUME SCINTILLATORS

The results of calculations presented in this section concern the detection efficiency of neutrons from reaction (1) and

Table 1

Comparison of measured [10] and calculated efficiencies of the long NE-213 scintillator ($100 \times 11.5 \times 6.5\ \mathrm{cm}^3$)

E_n (MeV)	Efficiency	
	Netter [10]	this work
2	0.48 ± 0.03	0.48
7	0.32 ± 0.05	0.30

other characteristics of the NE-213 scintillator shown in Fig.1. The isotropic neutron source (i.e., the target geometry) as well as the neutron beam case were considered to complete the information. The calculations were performed for two versions of the detector, with scintillator sizes: A) diameter 50 cm, height 43 cm; B) diameter 68.5 cm and height 54 cm. The active volumes were 84 and 200 l, respectively.

In Tables 2 and 3 we present the calculated efficiencies of neutron detection for different registration thresholds, for target and beam geometry, respectively. The attenuation of light was taken into account according to the procedure described in the preceding section. The total relative error of the calculated values of efficiency due to statistical errors, errors of input cross sections data, uncertainty in the relations: particle energy - light output, simplifying assumptions used in the calculation algorithm etc., is estimated to be less than 2%. As can be seen from Tables 1 and 2 the efficiency of detectors with so large active volumes seems high enough for its successful application to investigation of rare processes which involve neutrons up to 15 MeV. It should be mentioned that more than two-fold increment of the scintillator volume increases the efficiency, when $E_{thr} = 0$, by less than 2% for the energy range 2.5-5.2 MeV and by about 5% for 14.1 MeV neutrons. The difference in the efficiencies of the 84 and 200 l detectors increases, for a given threshold, with the neutron energy and reaches the maximum value of 15% for $E_n = 14.1$ MeV and $E_{thr} = 0.6$ MeV.

Fig.5 shows the pulse-height distributions for 2.5 and 5.2 MeV neutrons, respectively, and for the scintillator of 200 l volume (version B). A good form of these spectra with a distinctive peak can be seen, as it was expected. It is possible, in general, to avoid the system of the $n-\gamma$ pulse-shape discrimination, using proper lower and upper energy threshold levels.

Similar spectra of neutrons from reactions (1c) and (1d) are shown in Figs.6 and 7, for both versions of the scintilla-

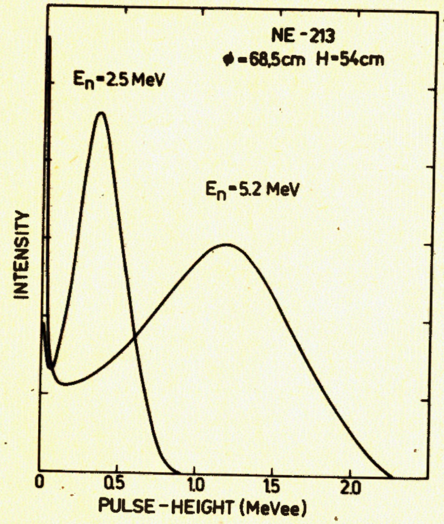

Fig.5. Pulse-height distributions obtained for 200 l NE-213 scintillator for 2.5 MeV and 5.2 MeV neutrons.

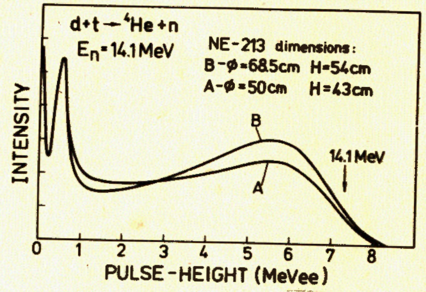

Fig.6. Pulse-height distributions from 84 l (curve A) and 200 l (curve B) scintillators, for 14.1 MeV neutrons. The peak in the low channels of spectrum is attributed to recoil α particles.

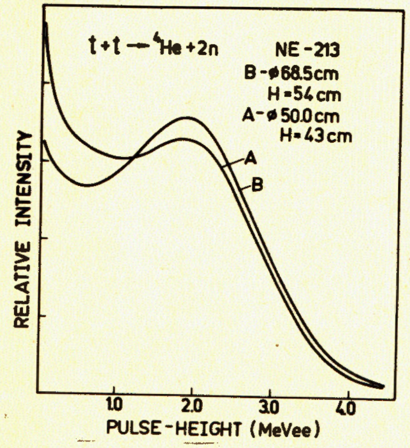

Fig.7. Pulse-height distributions from 84 l (curve A) and 200 l (curve B) scintillators, for (t + t)-reaction neutrons.

tor (84 and 200 l). The pulse-height spectrum for $t + t \to \alpha + 2n$ reaction (Fig.7) is the summary spectrum of both produced neutrons. No interaction between reaction products in the final state was considered, i.e., the initial energy and momentum distributions of neutrons were determined by the reaction phase-space.

Table 2

Efficiencies of neutron detection of the large-volume NE-213 scintillator for neutrons from different reactions as the function of the threshold level (case of target geometry). Scintillator sizes: A) Ø = 50 cm, H = 43 cm; B) Ø = 68.5 cm, H = 54 cm (see Fig.1)

$d+d \to {}^3He+n$ E_n=2.5 MeV			$\mu^-+p \to n+\nu_\mu$ E_n=5.2 MeV			$d+t \to {}^4He+n$ E_n=14.1 MeV			$t+t \to {}^4He+n+n$ *) $\langle E_n \rangle$ = 4.5 MeV		
E_{thr} MeVee	A	B	E_{thr} MeVee	A	B	E_{thr} MeVee	A	B	E_{thr} MeVee	A	B
0.0	.935	.943	0.0	.892	.910	0.0	.792	.840	0.0	.990	.993
0.1	.871	.901	0.2	.773	.841	0.2	.619	.701	0.2	.909	.938
0.2	.782	.815	0.4	.710	.767	0.4	.597	.680	0.4	.843	.885
0.3	.644	.666	0.6	.640	.701	0.6	.556	.636	0.6	.783	.835
			0.8	.564	.618	0.8	.525	.604	0.8	.721	.792
						1.0	.505	.589			
						1.5	.468	.556			
						2.0	.435	.522			

*) Efficiency in this case is related to the reaction events.

Table 3

Efficiencies of neutron detection for the large-volume NE-213 scintillator - beam geometry case. The neutron beam of diameter of 6 cm enters the detector through the channel shown in Fig.1. Scintillator size: Ø = 68.5 cm, H = 54 cm

E_n = 2.5 MeV		E_n = 5.2 MeV		E_n = 14.1 MeV	
E_{thr} MeVee	ε	E_{thr} MeVee	ε	E_{thr} MeVee	ε
0.0	.998	0.0	.983	0.0	.916
0.01	.994	0.05	.956	0.2	.797
0.02	.992	0.1	.948	0.4	.780
0.05	.989	0.2	.942	0.6	.734
0.1	.985	0.4	.915	0.8	.700
0.2	.933	0.6	.849	1.0	.683
0.3	.773	0.8	.749	1.5	.651
0.4	.530	1.0	.596	2.0	.617

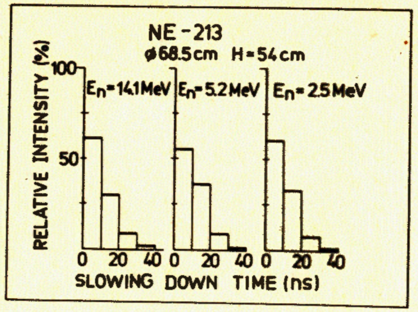

Fig.8. Slowing-down time of neutrons in the 200 l NE-213 scintillator. The cut-off neutron energy is 0.25 MeV.

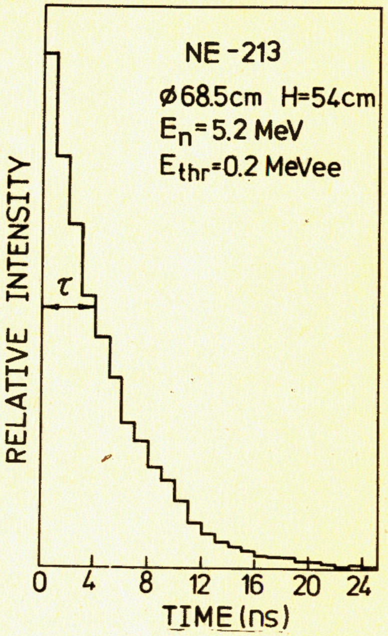

Fig.9. Time response function of the 200 l scintillator for 5.2 MeV neutrons and for detection threshold 0.2 MeVee. The time resolution τ is marked.

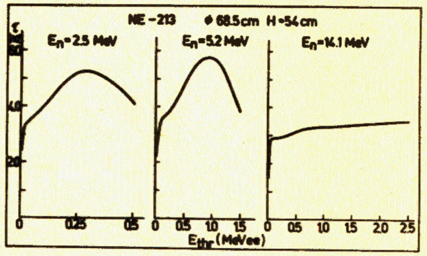

Fig.10. Time resolution of the 200 l scintillator vs detection threshold, for 2.5 MeV, 5.2 MeV and 14.1 MeV neutrons, respectively.

Figures 8 and 9 present different time distributions. The first one shows the slowing-down time, i.e., the time at which the energy of the neutron falls below the energy limit E_{lim} or the neutron leaks out of the scintillator. The energy E_{lim} = = 0.25 MeV was selected to make negligible the light-output from the residual neutron energy. As can be seen, the slowing-down time of the majority of neutrons is less than 20 ns, irrespective of their initial energy. The second figure (Fig.9) shows the example of the time response function of the scintillator, i.e., the time at which the light-output exceeds a given detection threshold E_{thr}. From such distributions the time resolution τ was determined. This time is presented in Fig.10 for the scintillator of 200 l volume, versus the detection threshold, for different energies of neutrons. The value

of about 6 ns is not exceeded in any case, so this time resolution is reasonable for muon catalysis investigation purposes.

5. CONCLUSIONS

Calculations of neutron detection efficiency and time characteristics of the large-volume NE-213 scintillators were carried out using the Monte-Carlo method. A high efficiency (60-90% for reasonable detection thresholds) and a sufficiently good time resolution (≲6 ns) characterize detectors with 80-200 l scintillator volume, the neutron energy being $E_n \lesssim 15$ MeV. So, these detectors may be successively applied in the fast-neutron experiments, in particular in investigations of μ-atom and μ-molecular processes for which the characteristic times are compared with the muon lifetime (τ_μ = 2.2x x 10^{-6} s). We suggest to use in this case the detector with ~100 l NE-213 volume, as no substantial quantitative differences in the efficiency are observed for the volume range 80-200 l.

The analysis of light attenuation effects by the scintillator itself allows us to conclude (see Fig.4) that no strong influence of these effects on the calculated detector characteristics is observed when γ-calibration procedure is used.

The authors are indebted to G.L.Mazny for useful discussions concerning the optimization of the computer code.

REFERENCES

1. Stanton N.R. Ohio State University, COO-1545-92, 1971.
2. Cecil R.A. et al. Nucl.Instr. and Meth., 1979, 161,p.439.
3. Verbinski V.V. et al. Nucl.Instr. and Meth., 1968, 65, p.8.
4. Poenitz W.H. Nucl.Instr. and Meth., 1973, 109, p.413.
5. De Leo R. et al. Nucl.Instr. and Meth., 1974, 119, p.559.
6. Nakayama K. et al. Nucl.Instr. and Meth., 1981, 190, p.555.
7. Gul K. Nucl.Instr. and Meth., 1980, 176, p.549.
8. Drosg M. Nucl.Instr. and Meth., 1972, 105, p.573.
9. Thornton S.T., Smith J.R. Nucl.Instr. and Meth., 1971, 96, p.551.
10. Netter P. et al. Nucl.Instr. and Meth., 1981, 185, p.165.
11. Harvey J.A., Hill N.W. Nucl.Instr. and Meth., 1979, 162, p.507.
12. Bystritsky V.M. et al. Zh.Eksp.Teor.Fiz., 1981, 80, p.1700. (English transl. Sov.Phys.JETP, 1981, 53, p.877).
13. Bystritsky V.M. et al. Prib.Tekn.Eksp., 1983, 3, p.42 (Instr.Eksp.Tech.).

14. Bystritsky V.M. et al. JINR, 1-7527, Dubna, 1973.
15. Bystritsky V.M. et al. Acta Phys.Pol., 1984, B15, 7, p.689.
16. Neutron Cross Sections. BNL-325, 2nd Ed., Supplement No.2, Physics-TID-4500, 1966.
17. Schmidt J.J. Neutron Cross Sections for Fast Reactor Materials, part II. Tables KFK 120, EANDC-E-354, 1982.
18. Del Guerra A. Nucl.Instr. and Meth., 1976, 135, p.337.
19. Kuijper P. et al. Nucl.Instr. and Meth., 1966, 42, p.56.
20. Annand J.R.M., Galloway R.B. Nucl.Instr. and Meth., 1983, 211, p.421.

Received by Publishing Department
on November 13, 1984.

Быстрицкий В.М., Возняк Я., Зинов В.Г. E1-84-735
Характеристики нейтронных детекторов
с большим объемом сцинтиллятора NE-213
для исследования мюонного катализа ядерных реакций синтеза

Для определения свойств и возможностей эффективного нейтронного детектора с большим объемом сцинтиллятора NE-213 нами был использован метод Монте-Карло. Спектры протонов отдачи, вычисленные эффективности для различных порогов регистрации и размеров сцинтилляторов представлены для нейтронов с энергией до 15 МэВ. Временные характеристики, такие, как временное разрешение, обсуждаются в данной работе. Показано, что учет ослабления света практически не существенен при вычислении эффективности регистрации нейтронов, если производить калибровку спектрометрических каналов с помощью стандартных источников γ-квантов. Детектор с объемом ~100 л предлагается использовать для исследования μ-атомных и μ-молекулярных процессов.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1984

Bystritsky V.M., Wozniak J., Zinov V.G. E1-84-735
Characteristics of the Large-Volume NE-213 Neutron Counters for Muon Catalyzed Fusion Investigation

The Monte-Carlo method was used to establish the properties and feasibility of a large-volume NE-213 scintillator as an efficient neutron detector. The recoil protons spectra, calculated efficiencies for different detection thresholds and scintillator sizes are presented for the neutron energy up to 15 MeV. The time characteristics, e.g., time resolution, are discussed. It is also shown that no strong influence of light attenuation by the scintillator itself on calculated efficiencies is observed, when gamma-calibration technique is used. The detector volume of ~100 l is suggested for application in investigations of μ-atom and μ-molecular processes.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1984