сообщения
объединенного
института
ядерных
исследований
дубна

E13-88-566

V.V.Filchenkov, L.Marczis

REGISTRATION EFFICIENCY OF A FULL-ABSORPTION NEUTRON SPECTROMETER

1988

1. INTRODUCTION

Successes have been reached in the past in the investigation and determination of characteristics of scintillation spectrometers for fast neutrons with relatively small scintillator volumes (V ≤ 1 l). Because of the necessity of succeeding the consecutive interactions of the neutrons with nuclei of hydrogen and carbon (n-p and n-C interactions), the nonlinear dependence of the light output function from the proton energy $L(E_p)$, and because of other difficulties Monte-Carlo calculations are widely used in this field (see ref.[1]).

There are fewer data concerning neutron spectrometers with large dimensions. For example in ref.[2] there are results regarding γ-spectroscopy only for detectors with dimensions not more than Ø 250x50 mm. In ref.[3] there are data of a large volume neutron detector (efficiency and pulse height), however they were obtained for the special "idealised" case of a narrow neutron beam oriented parallel to the axis of the detector. There are calculations regarding the efficiency and pulse height spectrum for a large volume neutron detector (V = 50-200 l) presented in ref.[4], however this detector was not realised, so cannot be compared with experiments.

It has been designed, realised and applied by our group for two years in muon catalysed fusion experiments a neutron spectrometer with a NE-213 scintillator* with a volume of V = = 24.1 l. The construction of the detector is described in ref.[5]. Also there were demonstrated the experimentally obtained pulse height spectra for γ-sources and for "quasi-monoenergetic" neutrons. This detector was planned for investigations of muon catalysed fusion reactions in deuterium:

$$d\mu + d \to dd\mu \to \begin{cases} {}^3He + n + \mu \\ {}^3He\mu + n \end{cases} \qquad (E_n = 2.45\ MeV), \qquad (1)$$

* *Product of Nuclear Enterprise, Edinburgh, Scotland.*

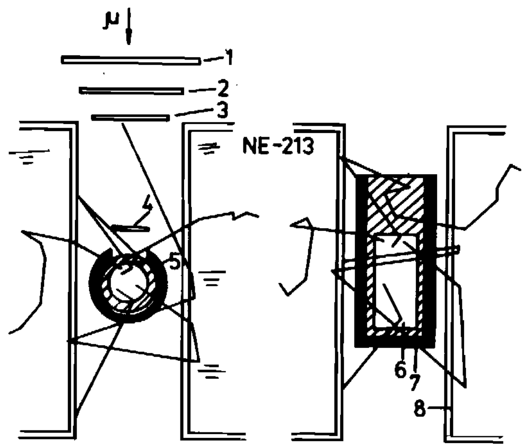

Fig.1. The scheme of the measurement. 1-5 - scintillation counters of the muon and electron detectors, 6 - gas target, 7 - walls of the target, 8 - teflon reflector. Soft lines are trajectories of neutrons produced in the target, modellised by the computer code.

in tritium:

$$t\mu + t \to tt\mu \to \begin{cases} {}^4He + 2n + \mu \\ {}^4He\mu + 2n \end{cases} \qquad (E_n = 0\text{-}10\ \text{MeV}), \qquad (2)$$

and possibly for investigations of muon capture by protons:

$$\mu^- p \to n + \nu_\mu, \quad (E_n = 5.2\ \text{MeV}). \qquad (3)$$

As mentioned in ref. [5], the use of a detector with high efficiency makes it possible to take advantage of the multiple feature of muon catalysis process. The increase of registration efficiency with increasing detector dimensions is connected not only with the increase of solid angle and that of probability of n-p interactions in the scintillator, but also with the decrease of the threshold, caused by the radical change of the pulse height distribution.

The scheme of the set up for investigation of process (1) is presented in Fig.1. As seen, the detector had two equivalent parts, symmetrically positioned to the deuterium gas target. The scintillators in our detectors have the dimensions Ø 310x160 mm. It is a special point of our experiments the use of high pressure targets (up to 1.5 kbar). The target holder was made of special steel (80% Ni, 16% Cr + 3% Mo, W and 1% Al, Ti, Nb) with the internal dimensions Ø 42 x 100 mm, the thickness of the walls was 9 mm at the sides, 12 mm at the bottom and 58 mm at the top. There was a scintillation detector between the target and the detector for the registration of muons and electrons. The thickness of the scintillator in it was 5 mm.

The aim of this work was to calculate the neutron registration efficiency and the pulse height distribution of the set-up for processes (1)-(3). Concrete results are presented here only for reaction (1), where it is possible already to make comparison with experimental results. The feature of experiments makes it necessary to take into account not only the consecutive n-p and n-C interactions in the scintillator, but also the scattering processes of neutrons in the deuterium and in the walls of the target and of detector 5, and in the teflon layer of the neutron detectors.

2. SCATTERING PROCESSES IN THE SCINTILLATOR

It is possible to share the calculations into two parts. At first, the characteristics of the detector, at second, the influence of the deuterium target and of the "walls" (so we call all of the intermediate materials between the target and the scintillators) were considered. Conserning the transfer of neutrons through the scintillators (C_8H_{10}), elastic n-p, elastic n-C interactions were taken into account. Cross section data were taken from ref. [6,7] and used in the table form. For elastic n-p interactions the angular distribution in the central of mass system was supposed to be isotopic (it is valid for $E_n \le 15$ MeV), and for n-C interactions data of ref. [7] were used. For the determination of the energy (E_n') and the scattering angle (ν') of the scattered neutron in the Laboratory system formulas

$$E_n' = E_n \cdot (a^2 + b^2 + 2 \cdot a \cdot b \cdot \cos\nu_{c.m.}), \qquad (4)$$

$$\cos\nu' = \sqrt{E_n / E_n'} \cdot (a + b \cdot \cos\nu_{c.m.}), \qquad (5)$$

were used. Here $a = m/m + M$, m is the neutron mass, M is the mass of the target nuclei (p or C), and $b = M/m + M$.

For each of the neutrons no more than 10 successive n-p interactions were considered. The recoil energy of protons $E_p = E_n - E_n'$ was transformed to light output L by means of the given $L = (E_p)$ function. The light output of all the scattering processes of the neutrons was summed. As experienced, only a little part of the neutrons (< 1%) interacted in 10 scatterings. Most of them leaked out of the detector earlier, or fell below a low energy threshold of 100 keV.

As light output function in first approximation dependence $E_{ee} = K \cdot E_p^{1.5}$ was used, which gives an agreement with data

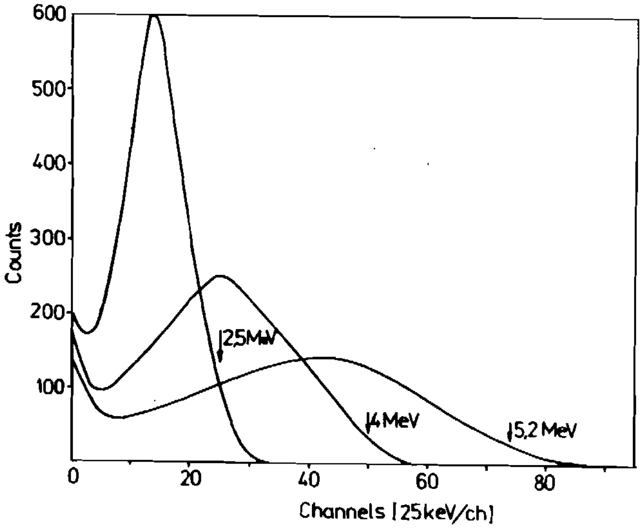

Fig.2. Pulse height spectra of the set-up for neutrons with E_n *= 2.45 MeV, 4 MeV and 5.2 MeV. The point source was positioned into the centre of the detector with dimensions 2×Ø 310×160 mm. The arrows show the energy limit of the recoil protons.*

of ref.[8] within 5%. (Here L as usually, is normalised to electron light output). For more detailed calculations data from tables of ref.[8] were used for $E_{ee}(E_p)$, and multiplied by a correction factor K, the value of which was determined by us in calibrational measurements[9]. Also from here were taken the parameters of the energy resolution function.

The spectra of our set-up for neutron energies E_n = 2.45, 4, and 5.2 MeV and with detector dimensions Ø 310x160 mm are shown in Fig.2, and the efficiencies of registration are presented in Table 1. To enhance the reliability of our results, calculations with two independent codes have been performed. An agreement within 1 2% has been achieved. In Fig.3 calculated and experimental spectra of "quasimonoenergetic" neutrons got from a Pu Be source (see ref.[9]) by time of flight method are presented. For each spectrum corresponds a group of neutron energies. As is seen there is a good agreement between experiments and calculations.

As is mentioned in ref.[6], formula

$$\varepsilon = 1 - e^{-n_p \sigma_{np} d} \qquad n_p \sigma_{np} \bar{d} \cdot (E_{th}^{ee}/E_n) \qquad (6)$$

in many cases may be used for a not bad at all estimation of neutron registration efficiency, even for large volume detectors. Here n_p is the density of hydrogen nuclei, σ_{np} is the n-p interaction cross section, $\bar{d}$ is the average path length of neutrons in the scintillator, E_{th} is the threshold energy

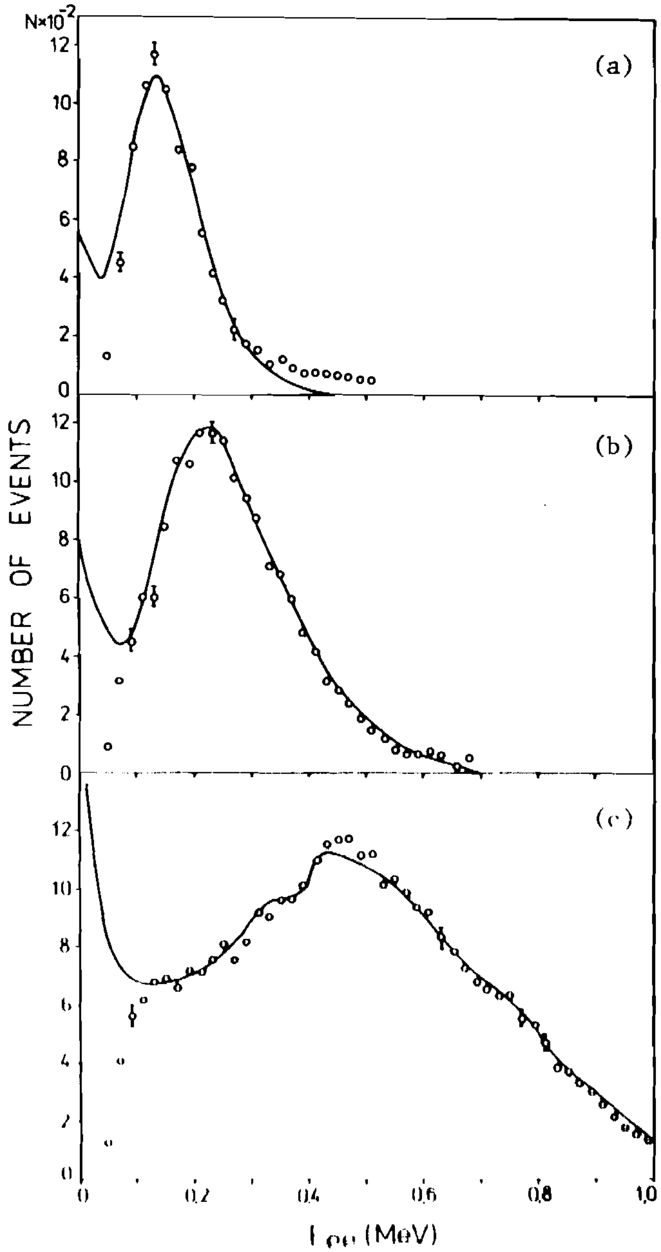

Fig.3. Spectra got by 238 Pu Be source by means of TOF method. The average energies are: (a) 1.8 MeV, (b) 2.5 MeV, (c) 4.[illegible] MeV. Lines are calculations.

Table 1

Calculated values of total efficiency (ϵ_0) and of efficiency (ϵ) when threshold was taken into account (E_{th}^{ee} = 100 keV) of a neutron detector with dimensions Ø310 × 160 mm. The source was positioned to the detector as shown in Fig.4 (distance s = = 0.1 cm)

Neutron energy (MeV)		2.45	4	5.2
Efficiency of registration ($\Omega = 4\pi$)	ϵ_0	0.843	0.771	0.742
	ϵ	0.763	0.724	0.695

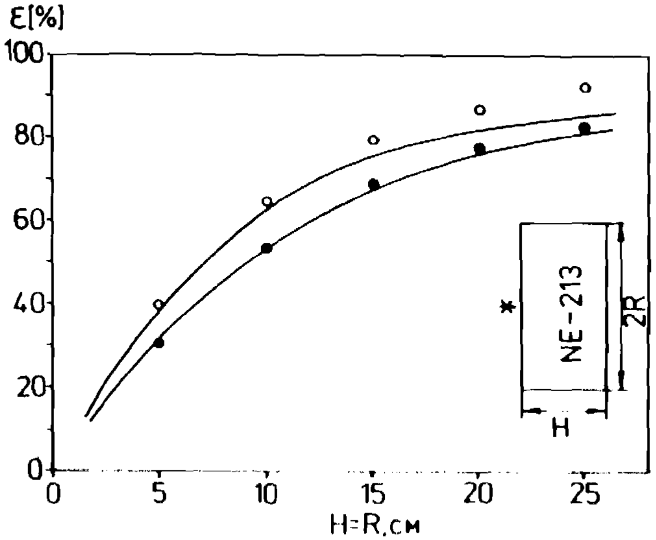

Fig.4. The efficiency of the detector (normalised to solid angle Ω = = 50%) in dependence on the dimensions. Lower line: calculation for E_n =5.2 MeV, upper line: for E_n 2.45 MeV. Points are estimations got by formula (6), E_{th}^{ee} 100 keV.

of recoil protons. In Fig.4 estimations obtained by formula (6) and results of Monte Carlo calculations on the dependence of the neutron registration efficiency on the size of the detector for E_n 2.45 MeV and 5.2 MeV are presented together (Here a point source was positioned into the centre of the detector, and E_{th} = 0.7 MeV).

As is seen, the disagreement between estimations got by (6) and the results of the Monte Carlo calculations is higher for E_n = 2.45 MeV and increases with increasing detector dimensions. Of course these estimations give a better fit of effici

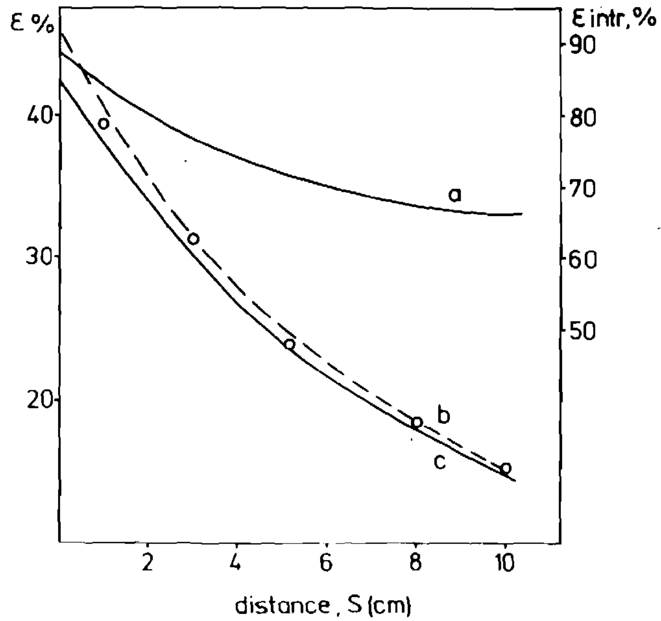

Fig.5. The efficiency of the detector in dependence on the distance from the neutron source a) of the bare scintillator, b) when scattering from one detector into the other is taken into account, c) without such kind of scattering (one detector). Points are simple estimations.

ency for thresholds in the region of relatively little amplitudes, which are connected with single interactions. In Fig.5 the dependence of the neutron registration efficiency of a detector with dimensions Ø310x160 mm on distance (s) between the neutron source and the detector is demonstrated. Also here are presented the results of simple calculations $\epsilon(s)$ (without threshold), in which the detector was supposed to consist of separated elements, and for each of them the efficiency was determined as the product of function $\epsilon_0 = 1 - \exp(-n_p \sigma_{np} \bar{d})$ and of solid angle. As is seen from the figure, there is a good agreement between simple and detailed calculations. Also in this figure are presented (devided by two) the data for two symmetrically to the source positioned detectors to illustrate the effect of scattering of the neutrons from one detector into the other. From these data follows that at s = 5.0 cm $\epsilon_0(s) \approx 25\%$, and with 100 keV threshold $\epsilon_0 \approx 20\%$. For comparison we mention that for a detector with R = 5 cm and H = 10 cm the same value is ≈ 1.5%.

3. SCATTERING IN THE TARGET AND IN THE WALLS

At the second step the influence of deuterium target and that of its walls and other intermediate media were studied.

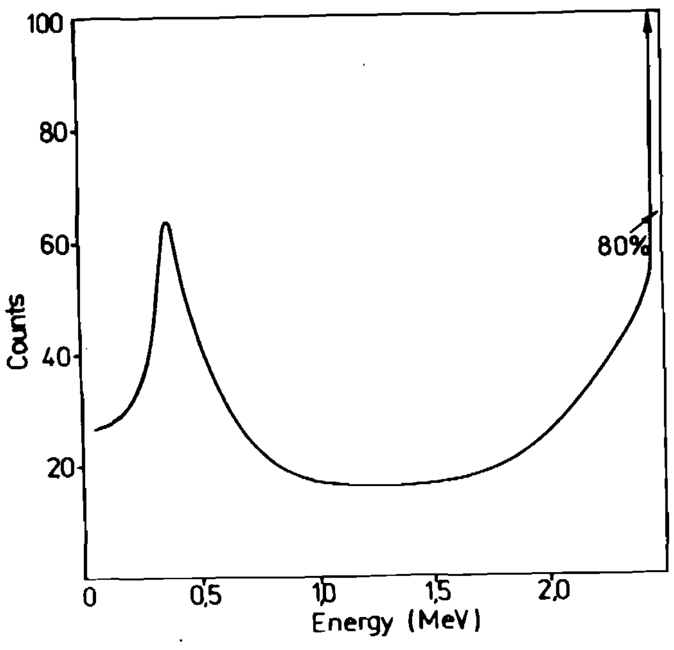

Fig.6. The influence of a deuterium target with dimensions Ø42 × × 100 mm, and p = = 1.5 kbar pressure on the neutron spectrum with initial energy E_n = = 2.45 MeV.

The main feature of n-d interactions is the sharp asymmetry of scattering in the central of mass system with a dominant backscattering (for $E_n < 2$–3 MeV). It causes a significant average energy loss of neutrons, so the efficiency of registration without threshold will rise, and in the case of real thresholds will decrease. Data of n-d cross sections were taken from ref.[10] in form of differential cross sections for E_n = 0.5, 1.0, 1.5, 2.0, 2.5 MeV. For the kinetics formula (4) was used, where M is the mass of the deuteron. In Fig.6 the influence of the deuterium target on the energy spectrum of neutrons with initial energy of E_n = = 2.45 MeV is show. The appearance of a peak in the small energy region according to almost full energy loss of the neutrons calls attention. That circumstance gave the base to investigate the pulse height spectrum of a full absorption neutron detector with a deuterised scintillator of type C_8D_{10}. Examples of using such kind of small volume detectors are known in the literature[11]. In Fig.7 the pulse height spectrum obtained by a C_8D_{10} scintillator with dimensions Ø 310x160 mm is compared with that obtained by a C_8H_{10} scintillator with the same dimensions. As is seen the conclusion can be drawn that the use of a deuterised scintillator in a large detector does not improve radically the line shape.

Investigating the interaction of neutrons in the "walls" of the target for simplicity a 80% Ni, 20% Cr composition was supposed, which may cause an error of ≲1%. The differen

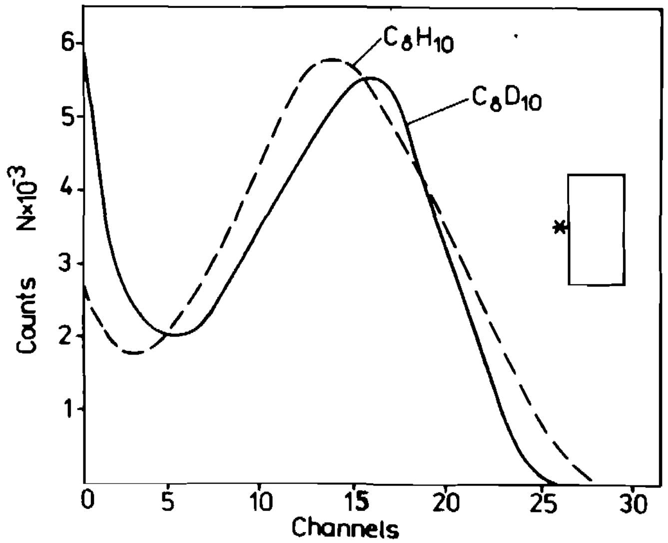

Fig.7. Neutron spectra of hydrogen containing (C_8H_{10}) and of deuterised (C_8D_{10}) scintillators. The spectra are normalized to equal amplitudes of maximum.

tial and total cross sections were taken from ref.[6,7]. The transfer of neutrons through the scintillator of dedector 5 was followed the same way as in the scintillator of the neutron detector, taking the appropriate chemical composition into account. The influence of the walls of this detector (1 mm steel) was neglected.

The modellisation of transfer of neutrons through the "walls" (so we call all of the intermediate media between the target and the detector) was performed as follows. Knowing the position of the walls and the coordinates of the last interaction of the neutron (or that of its production in reaction (1)) and the direction of its flight, the coordinates of crossing the nearest wall were determined. Knowing the thickness of the walls and the interaction cross section of the neutrons, it was determined, whether there was any interaction in the wall or not. When yes, than the coordinates of interaction, the energy and the direction of flight of the neutron were determined, and the process was repeated. If not the case, then the coordinates of crossing the following wall were determined and used as starting points.

This feature of the calculations was used for effective checking of the "geometrical" part of the code. In more detail: all the densities of nuclei in the walls were set to zero, that is no interaction of neutrons in them was supposed. The crossing points with every one of the walls were determined as earlier, using the last crossing point as starting point. The results obtained this way (n_z − 0) practically agreed with those obtained at the first step for the bare scintillator. At last we mention that the calculations were performed

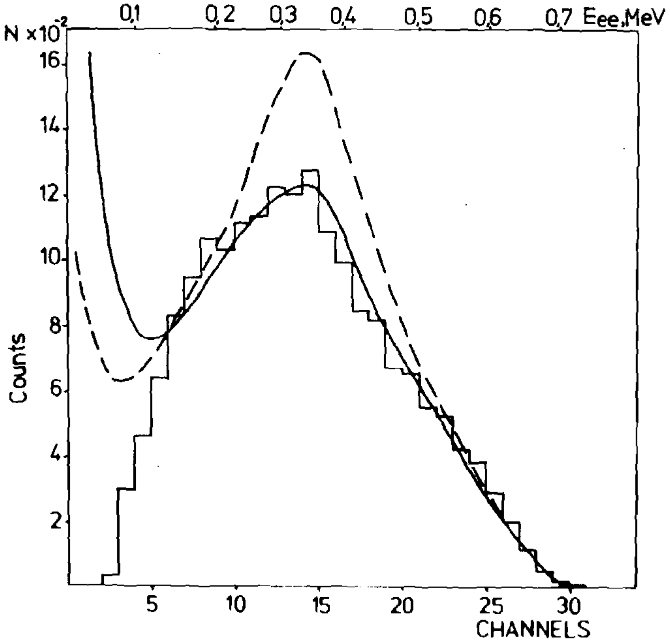

Fig.8. Pulse height spectrum of neutron events together with results of Monte-Carlo calculations. Dashed line is the calculation for point source and bare scintillator; solid line, for real conditions. The histogram: experimental distribution.

by two independent codes, determining the coordinates of crossing the walls by two different ways. There was an agreement between the results within 2-3%.

In Fig.8 experimental spectra of neutrons with an energy of E_n = 2.45 MeV produced in reaction (1) are shown for the bare scintillator (a), and for the case when deuterium (p=1.5 kbar) and all of the walls are taken into consideration (b). A significant influence of deuterium on the spectra can be observed, however the metallic walls cause only a small change of the pulse height spectra and of total efficiency. In the calculations a distance of L = 5.5 cm between the target axis and the detector surface was used, according to the experimental conditions in the investigations of process (1). Because in first experiments only one half of the detector was used, only results obtained for this case are demonstrated. Table 2 includes the results according to calculations of total efficiency. Ω means the geometrical efficiency of the scintillator; ϵ_0 is the total efficiency of the scintillator; ϵ_D is the same with the consideration only of the deuterium; ϵ with the consideration of the deuterium and all of the walls. We mention that there is a good agreement between the value of Ω^{MC} =13.6% obtained by Monte Carlo code and that obtained by formula $\Omega = 1/2\cdot(1 - (\sqrt{1 + R^2/H^2})^{-1})$, and between the values of ϵ_0^{MC} and that obtained by simple calculations.

Table 2

Characteristic data of calculated registration efficiencies with the energy of E_n = 2.45 MeV at experimental conditions of investigating process (1) (E_{th}^{ee} = 100 keV)

Geometrical efficiency, Ω (without taking into account the deuterium and the walls	Efficiency, ϵ_0 calculated without the deuterium and the walls		Efficiency, ϵ_D only deuterium (target size: Ø42x x100 mm. p= =1.5 kbar)		Efficiency, ϵ deuterium and all of the walls taken into account	
	No	/100 keV threshold	No	/100 keV threshold	No	/100 keV threshold
0.336	0.234	0.205	0.248	0.185	0.249	0.173

The results of calculations presented in Table 2 were used in the evaluation of experimental data. We estimate the relative error of our calculations not to be more than 3%.

4. CONCLUSIONS

Modellisation of experimental spectra and calculations on neutron registration efficiency of large-volume (V = 24.1 l) neutron detector by means of Monte Carlo method were performed. They may be useful not only for the above mentioned experiments, but also for other works in the field of muon catalysis. The results obtained by the code agree with simple estimations and calculations within a few percent, which may help other authors in choosing the sizes of their detectors for investigations of different physical processes.

At last we mention, that the created code can be easily adopted to other geometrical conditions of the experiment, and to other energy intervals (≤ 10 MeV) of neutrons. The code may be used even in cases when the initial spectrum of neutrons has a complicated form. This last circumstance is important for example in investigating process (2) in liquid tritium, where a direct measurement of ϵ is possible. In this case the comparison of calculations with experiments gives information about the form of spectra of neutrons from process (2) which is of interest from the point of view of nuclear physics.

The authors are grateful to E.A.Pasyuk for valuable discussions.

REFERENCES

1. Thornton S.T., Smith J.R. - Nucl.Instr.and Meth., 1971, 96, p.551.
2. Dietze G., Klein H. - Nucl.Instr. and Meth., 1982, 193, p.549.
3. Poenitz W.H. - Nucl.Instr. and Meth., 1973, 109, p.413.
4. Bystritsky V.M., Wozniak J., Zinov V.G. - Nucl.Instr. and Meth., 1985, A241, No.2,3, p.532.
5. Dzhelepov V.P., Zinov V.G. et al. JINR Preprint 13-87-476, Dubna, 1987 and Nucl.Instr. and Meth., to be published.
6. BNL-325 Vol. IIA, Suppl. 2, 1966.
7. BNL-400 Bol. I-II, 1970.
8. Dekempeneer E. et al. - Nucl-Instr. and Meth., 1987, A256, p.489.
9. Filchenkov V.V., Konin A.D., Rudenko A.I. JINR Preprint 13-88-567, Dubna, 1988.
10. Horsley A. Nuclear Data A4, 1968, p.321-357.
11. Gunder O.A., Malinovskaia S.A., Teslia L.E. - PTE, 1971, No. 78, p.24.

Received by Publishing Department
on July 26, 1988.

Фильченков В.В., Марцыш Л. E13-88-566

Эффективность регистрации нейтронов спектрометра полного поглощения

Созданы программы расчетов и проведены вычисления методом Монте-Карло аппаратурных спектров и эффективности регистрации нейтронов большими /объем сцинтиллятора 24.1 л/ нейтронными детекторами. Показано, что во многих случаях простые оценки и вычисления воспроизводят эффективность /в том числе и с учетом порога/ с точностью нескольких %. Приведены формы линии для E_n = 2,45; 4 и 5,2 МэВ /при E_n = 2,5 МэВ также и для дейтерированного сцинтиллятора/. Представлены конкретные результаты для нейтронного спектрометра 2x⌀310x160 мм, используемого в ЛЯП, ОИЯИ, в экспериментах по изучению процесса мюонного катализа реакции синтеза d+d.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1988

Filchenkov V.V., Marczis L. E13-88-566

Registration Efficiency of a Full-Absorption Neutron Spectrometer

A Monte-Carlo code was created and used for modellisation of experimental spectra and of neutron registration efficiency by means of a large volume neutron detector (V = 24.1 l). As is shown, in many cases simple estimations and calculations (also when threshold is taken into account) agree within a few %. Pulse height spectra at E_n = 2.45, 4 and 5.2 MeV (at E_n = = 2.45 MeV also for a deuterised scintillator) are presented. Results for a neutron spectrometer with dimensions 2x ⌀310x160 mm, used at JINR for investigations of muon catalysed fusion process d+d are demonstrated.

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

Communication of the Joint Institute for Nuclear Research. Dubna 1988