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NEUTRON MULTIPLICITY DISTRIBUTION FOR THE MUON CATALYZED FUSION REACTIONS

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1 Introduction

The MCF experimental study is being conducted now on the JINR phasotron by a large international collaboration (the project MU-CATALYSIS). Recent results have been published in [1], [2] and [3]. The scheme of this process is shown in Fig. 1.

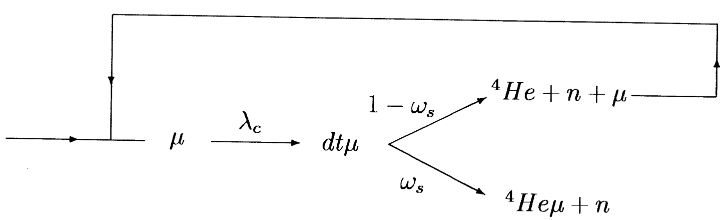

Figure 1: The scheme of the process of the multiple muon catalysis in the D-T mixture

A negative muon stopped in the D-T mixture can cause up to 100 d+t fusion reactions in which of them a 14 MeV neutron escapes. Intensity of the process is determined by the cycling rate (λ_c). It can be $\geq 100\,\mu s^{-1}$ under optimal conditions. Since the muon disappearance rate is $\lambda_0 = 0.455 \cdot \mu s^{-1}$ and relative muon losses for its sticking to helium are $w \equiv \omega_s + \Delta w \sim 1\%$ one muon can cause ≥ 100 fusion neutrons. (Here ω_s is related to the "main" $d + t$" reaction and Δw to the accompanying $d + d$ and $t + t$ reactions.

Novel methods are used in [1], [2] and [3] both to register the fusion reaction and to analyze the data. The main parts of the experimental set-up are a high pressure tritium target and a full absorption neutron spectrometer [4], which consists of two identical large scintillation detectors (ND) ($\phi 31\,cm \times 15\,cm$) symmetrically arranged around the target. To avoid the distortion caused by the pile-up effects flash ADC are used to measure *charge* Q from the neutron detectors. The number of *detected* neutrons is extracted using the value of the *unit charge*, q, which is related to a single neutron. The unit charge is measured in a special calibration exposure. The neutron detection efficiency ϵ was calculated in [5].

2 Motivation

In one of the novel analysis methods the neutron multiplicity (number of detected neutrons, k, per muon) is considered. Neutrons are selected in some definite interval T where muons do not disappear. Analysis of the extensive experimental data [1], [2], [3] revealed a high efficiency of the multiplicity method. One of the advantages of the method is that it does not require the mu-decay electron normalization. In principle, it is not necessary to detect the electron at all if one analyzes only the "long" (duration $> T$) neutron series. It is especially important for our future experiments with the target of superhigh density, whose walls have low electron transparency.

According to [6] the multiplicity distribution would be a sum of two terms. One of them, the Gaussian (Poisson) with the mean $m = \epsilon_n \Lambda_c \cdot T$, corresponds to the events without sticking, and the other, depending on w and falling with k, is the distribution of events with muon sticking:

$$N(k) = N_1 \cdot [f(k) + (1 - w/\epsilon_n)^m \cdot g(k; m)], \quad (1)$$

where N_1 is the total number of the first detected neutrons in the interval T, $g(k; m)$ is a Gaussian and $f(k)$ determined in the interval $k \leq m$ is described by

$$f(k) = y_{k-1} - y_k = y_1 \cdot [1 - y_1 \cdot (1 - \omega)] \cdot [y_1 \cdot (1 - \omega)]^{k-1},$$

where $y_1 = \epsilon_n \Lambda_c / \lambda_n = (1 - w/\epsilon_n - w)^{-1}$ is the relative yield of the first detected neutrons.

Original expression (1) is "phenomenological" and approximate. Surprisingly, it describes rather well the multiplicity distributions in a wide interval of m. So, for $m = 8 - 40$ fit of the appropriate Monte-Carlo (M-C) spectra with formula (1) gives the results coinciding with the predicted ones within $3 - 4\,\%$.

Formula (1) played a historical role in the multiplicity method substantiate and in getting the preliminary results [1]. Of course, the accurate analysis needs a rigorous expression for the multiplicity distribution true in the entire range of m. Each author obtained it independently by the same method which is described in the next section.

3 Rigorous expression for the multiplicity distribution

The differential time distribution of the kth detected neutrons can be presented as

$$n_k(t) = \int_{x=0}^{x=t} n_{k-1}(x) \cdot (1-w) \cdot n_1(t) \cdot dx,$$

If one takes into account that [7]

$$n_1(t) = (\epsilon\lambda_c) \cdot e^{-\lambda t}; \qquad \lambda = \lambda_c \cdot (w + \epsilon - w\epsilon)$$

then one obtains the expression

$$n_k(t) = (\epsilon\lambda_c)^k \cdot (1-w)^{k-1} \cdot e^{-\lambda t} \frac{t^{k-1}}{(k-1)!}$$

Note that its form is the same as for "physical" neutrons ($\epsilon = 1$).

The yield of the kth detected neutrons in the time interval $0 \le t \le T$ is

$$y_k = \int_0^T n_k(t)dt = \frac{(\epsilon\lambda_c)^k \cdot (1-w)^{k-1}}{(k-1)!} \cdot I_{k-1}^T,$$

where

$$I_{k-1}^T \equiv \int_0^T t^{k-1} \cdot e^{-\lambda t} \cdot dt. \qquad (2)$$

The yield of the k neutrons (multiplicity) is

$$f(k) = y_k - y_{k+1} = \frac{(\epsilon\lambda_c)^k \cdot (1-w)^{k-1}}{(k-1)!} \cdot [\frac{w}{\epsilon + w - \epsilon w} \cdot I_{k-1}^T - \frac{\epsilon\lambda_c(1-w)}{k\lambda} \cdot T^k \cdot e^{-\lambda T}]$$

Disclosing the integral (2) we finally obtain

$$f(k) = \frac{[\epsilon(1-w)]^k}{(\epsilon + \omega - \epsilon\omega)^k} \cdot P(k) + \frac{[\epsilon(1-w)]^{k-1} w}{(\epsilon + \omega - \epsilon\omega)^k} \cdot F(k) \qquad (3)$$

where $P(k)$ is the Poison distribution with the mean $m = \lambda T$

$$P(m) = \frac{(\lambda T)^k}{k!} \cdot e^{-\lambda T}$$

and

$$F(k) = 1 - e^{-\lambda T} \sum_{i=0}^{k-1} \frac{(\lambda T)^i}{i!}$$

Simulated multiplicity distributions and their fit with function (3) are shown in Fig. 2. Both spectra were calculated by the M-C method with the parameters

$$\epsilon = 0.2, \qquad w = 0.005, \qquad T = 2\,\mu s.$$

Two meanings of the cycling rate were used: $\lambda_c = 20\,\mu s^{-1}$ (for the left picture) and $\lambda_c = 100\,\mu s^{-1}$ (for the right picture). Fit of these distribution yields the values $\epsilon\lambda_c = 4.04(12)\,\mu s^{-1}$, $w/\epsilon = 0.0224(23)$ and $\epsilon\lambda_c = 20.26(5)\,\mu s^{-1}$, $w/\epsilon = 0.0242(5)$ for the left and right spectra respectively. They are in a good agreement with the expected values $w/\epsilon = 0.025$, $\epsilon\lambda = 4.0\,\mu s^{-1}$ and $\epsilon\lambda = 20.0\,\mu s^{-1}$.

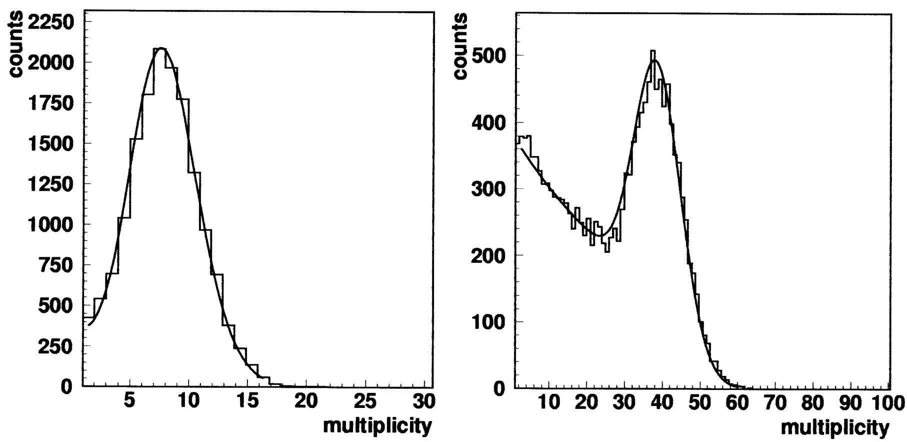

Figure 2: Simulated multiplicity distributions (histograms) and their fit (lines) with formula (3)

4 Diffusion of measured multiplicity distributions

Previous consideration (formulae and M-C simulation) were related to an "event mode", where the number of detected neutrons were considered. Really the distributions of the neutron detector *charge* were measured in the experiments [1], [2] and [3] and were normalized by the *unit charge* to obtain a multiplicity distribution. Obviously, this leads to diffusion of the measured spectra as compare with the ones obtained in the "event mode".

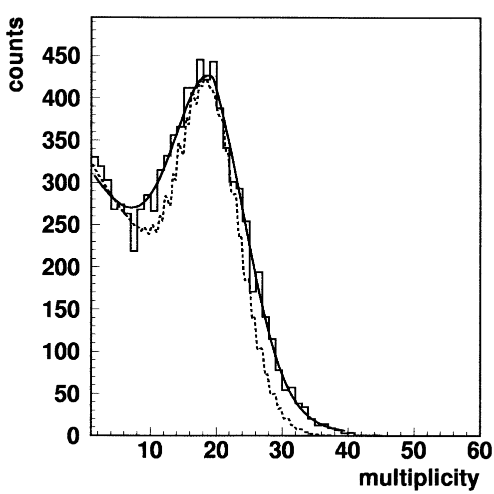

Figure 3: Experimental multiplicity distribution (charge per muon) measured in one of the exposures with a D/T mixture (histogram). The dashed line represents the dependence according to "event mode" (formula (3)). The full line corresponds to the optimal fit with the Gaussian distortion of the distribution taken into account.

To know the character of this diffusion one should take into account the response function of the neutron detector. In the first approximation the response function can be presented as uniformly distributed between the threshold and the maximum charge value. For this simplest case the dispersion function is Gaussian and requires that the expression for the multiplicity should be obtained as convolution of formula (8) with the Gaussian function. The result of the fit of some experimental multiplicity spectra is shown in Fig. 3. The Gaussian width was varied to obtain the best agreement between the experiment and calculations. In the same figure the appropriate "event mode" distribution (3) is shown by the dashed line.

The real response function differs from the uniform one mainly by presence of the intensive low-energy (charge) part ("tail") [5]. This can cause a deviation of the distortion function from the Gaussian and, hence, possible systematic errors. To clarify the situation the following was done:

1. We carried out the M-C calculations of the multiplicity distribution with the real response function of the neutron detector [8] for $w = 0$ (only "unsticked" events were considered). The data obtained for several values of a threshold (TH) were fitted with a Gaussian. It turned out that even for $TH = 0$ the obtained spectra are well described by a Gaussian. This case is presented in Fig. 4. The fit parameters are $m = 78.9(3)$ (80.0 is expected), $\sigma = 10.6(2)$, $\chi^2 = 42/57$.

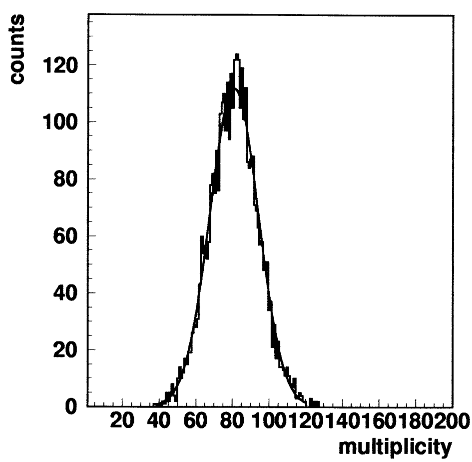

Figure 4: Multiplicity distribution simulated for the real response function of ND for a threshold $TH = 0$. Line represents the fit with the Gaussian.

2. For one of the experimental exposures made with the D/T mixture long neutron series were selected so that the time of the last detected neutron was $t_n^{last} > T$. For such events multiplicity distribution was created for the time interval T and fitted with a Gaussian. The results are presented in Fig. 5.

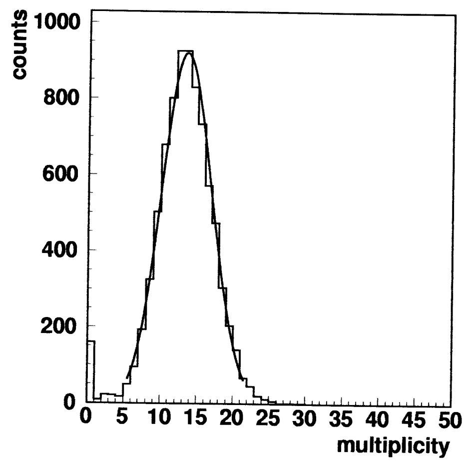

Figure 5: Experimental multiplicity distribution accumulated for the time interval $T = 1\,\mu s$ and selected under criteria $t_n^{last} > T$. The line is the Gaussian with the optimum parameters found in the fit.

As is seen from Figures 4,5 both distributions are well described by the a Gaussian. It follows from our consideration that the possible systematic error of λ_c in our analysis of the multiplicity distributions does not exceed $3 - 4\%$.

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References

[1] *Yu.P. Averin et al.,Procedings of the International Symposium on Exotic Atoms and Molecules and Muon Catalyzed Fusion (EXAT98), Hyperfine Interact. 118 (1999) 111.*

[2] *ibid, p. 121*

[3] *V.R. Bom et al., Hyperfine Interact., 119(1999)103.*

[4] *V.P. Dzhelepov et al., Nucl. Instr. Methods A 269(1988)634. V.V. Filchenkov, A.D. Konin, A.I. Rudenko, Nucl. Instr. Methods A 294(1990)504.*

[5] *V.R. Bom and V.V. Filchenkov, Hyperfine Interact., 119(1998)365.*

[6] *V.V. Filchenkov, Muon Catalyzed Fusion, 7(1992)409.*

[7] *V.G. Zinov, L.N. Somov, V.V. Filchenkov, Nucl. Instr. Methods, 228(1984)174.*

[8] *V.V. Filchenkov, A.E. Drebushko, A.I. Rudenko. Nucl. Instr. and Meth. A 395 (1997) 237.*

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Распределение по множественности нейтронов
для процесса мюонного катализа

Получено строгое выражение для распределения по множественности нейтронов в процессе мюонного катализа. Рассмотрены вопросы его использования в анализе экспериментальных данных.

Работа выполнена в Лаборатории ядерных проблем им. В.П.Джелепова ОИЯИ.

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Neutron Multiplicity Distribution
for the Muon Catalyzed Fusion Reactions

A rigorous expression for the neutron multiplicity distribution in the muon catalyzed fusion (MCF) reactions is obtained. Some problems of its use in the experimental data analysis are considered.

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

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