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ON THE CORRECT DETERMINATION OF THE MCF PARAMETERS

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1 Introduction

Extensive experimental studies of the muon catalyzed fusion (MCF) reactions

$$dt\mu \longrightarrow {}^4He + n + \mu \tag{1}$$

$$dt\mu \longrightarrow {}^4He\mu + n \tag{2}$$

are being carried out at the JINR Phasotron in Dubna.

Starting with the highest density of the D/T mixture (liquid) [1] we continued our research in a wide region of the mixture temperature and density [2]. Making measurements with a low-density mixture one met with a task of how to use most effectively the muon beam intensity. On the other hand, we continue foundation and development of our analysis methods. The present article is devoted to these problems.

The scheme of our experimental set-up is shown in Fig. 1. Wire counters (WC)

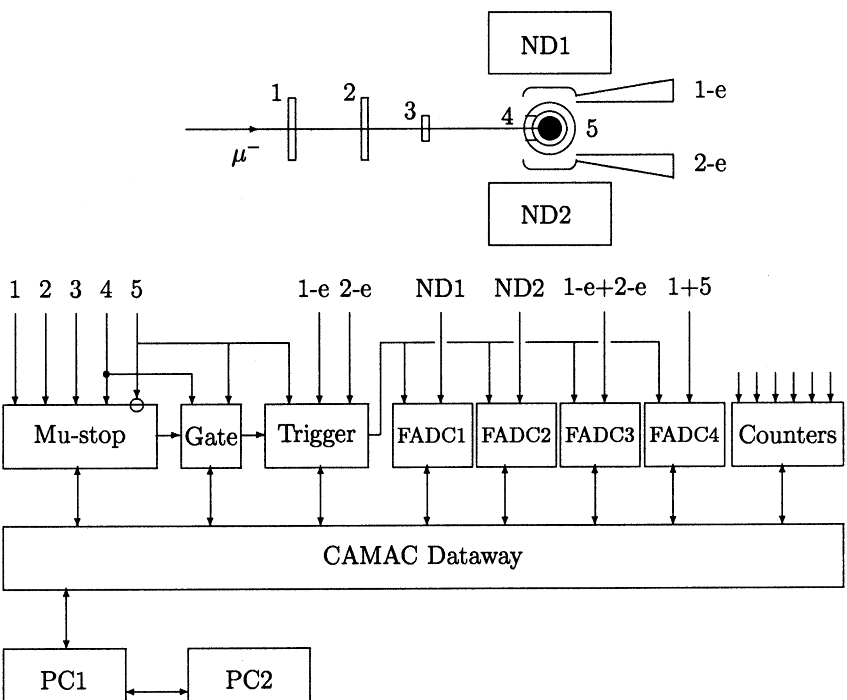

Figure 1: Scheme of the experiment.

4 and 5 serve as detectors for muons and μ-decay electrons respectively. Full absorption neutron detectors $ND1$ and $ND2$ are to detect neutrons from reactions

(1), (2). Signals from these detectors are registered by flashes ADC giving the time sequences of the signal amplitudes.

Three different ways are used by us in the data analysis to obtain the effective MCF parameters: a cycling rate (λ_c) and effective muon losses (W). The latter is mainly determined by the muon sticking to helium in reaction (2) and includes the losses in the accompanied $d+d$ and $t+t$ reactions. The most popular and practically only method used by most groups involved in a study of the $d+t$ MCF process [3, 4, 5] is so-called "standard" method where the yield and time distribution of all detected neutrons from reactions (1), (2) are registered and analyzed. In this method λ_c is determined from the normalized neutron yield

$$\lambda_c/\lambda_n = N_n/(\epsilon_n \cdot N_e), \tag{3}$$

where N_n and N_e are the numbers of detected neutrons and electrons, ϵ_n is the neutron detection efficiency and λ_n is the slope of the neutron time spectrum

$$dN_n/dt = \epsilon_n \cdot \lambda_c \cdot exp(-\lambda_n \cdot t). \tag{4}$$

With the thus obtained λ_c, W is extracted from the slope of the neutron time spectrum (4) $\lambda_n = \lambda_0 + W\lambda_c$, where $\lambda_0 = 0.455\ \mu s^{-1}$ is the muon decay rate.

In addition to the "standard" method two novel methods are suggested and successfully employed by the Dubna group [1, 6, 7]: "multiplicity" and "$t_e - t_n$" methods. In the "multiplicity" method the number of neutrons k on a definite interval T is analyzed for the events selected under the condition $t_e > T$, where t_e is the electron time. The corresponding distribution consists of two terms. One of them is gaussian (Poisson) with the mean $m = \epsilon_n \cdot \lambda_c \cdot T$ which determines the cycling rate. The character of the other part, falling with k, is determined by the value of W.

Finally, in the "$t_e - t_n$" method the distribution of the time intervals between the electron and the last detected neutron is considered. It has a form of two exponents, "fast" and "slow" $A_f \cdot exp[-(\lambda_0 + \gamma_n) \cdot t] + A_s \cdot exp(-\lambda_0 \cdot t)$, where $\gamma_n = \lambda_c \cdot (\epsilon_n + W - \epsilon_n W)$. Here the cycling rate is determined from the slope of the fast component and W is extracted from the ratio of the amplitudes A_s and A_f. Below we will consider only "standard" and "multiplicity" methods.

The statistical power is identical for all methods mentioned and is limited by the number of electrons. Indeed, in the standard method the electron number is directly involved in expression (3) for the cycling rate. The statistics for the other two methods is the number of the first or last detected neutrons, which is approximately equal to the electron number for the real experimental conditions. That is why it is important to conserve as much electron statistics as possible when the selection criteria are applied. This problem is considered in the present article.

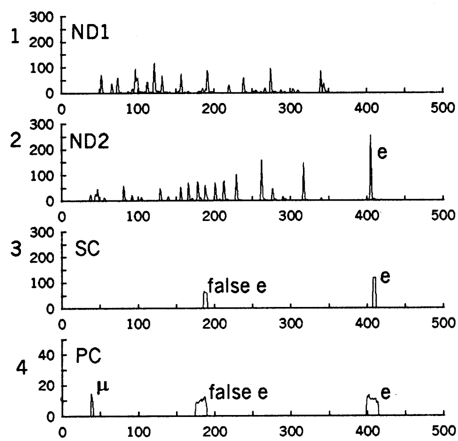

Figure 2: Flash ADC signal for a single muon with a "false" electron.

2 Selection criteria for the electron identification

A serious problem in the MCF data analysis is how to distinguish the real electron from the false one. Under the conditions when one muon can cause up to 100 reactions (1) it is possible to detect a neutron by the electron detector and accept it as an electron. Contrary to measurements of other groups, we detect electrons with a proportional wire counter, which is very low sensitive to neutrons. However, even in this case the fraction of the false electrons caused by the neutron counts is noticeable.

Examples of the signals on the flashes ADC corresponding to wire counters 4, 5 and the neutron detectors are presented in Fig. 2. For clarity, we have selected the events with simultaneous electron detection both by the WC and the neutron detector. The false electron, placed "inside" the neutron series, is clearly seen in the figure.

Of course, the number of the false electrons is small relative to the real ones. The visible effect is manifested only in the electron time spectrum which slope becomes more sharp. However, we could clearly separate the false electrons. For this we select the events with the real electron (the procedure for its confident identification will be explained later) and plotted the time distribution for all WC signals excluding the real electron signal. Such distribution for one of the D/T exposures is presented in Fig.3 (left) together with the neutron time spectrum measured in the same exposure. As seen from this figure, the characters of the both spectra are similar that confirms the origin of the false electrons. For comparison the false electron time spectrum is shown in the same figure (right) plotted for the pure deuterium exposure. This is

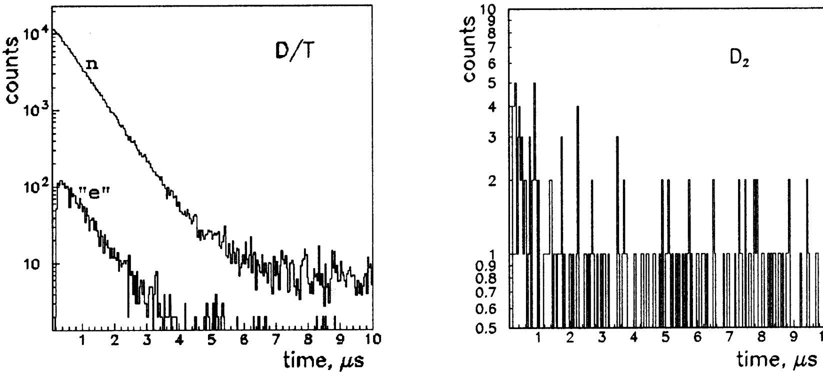

Figure 3: Left: time distribution of false electrons and neutrons measured in the D/T exposure. Right: time distribution of false electrons in the D_2 exposure.

practically the accidental background.

The condition of this exposure (relative density of the D/T mixture $\varphi = 0.9$ of liquid hydrogen density and tritium concentration $C_t = 0.31$) corresponds to the high neutron yield per muon (electron): $n \equiv N_n/N_e \simeq 100$. As follows from Fig.3, the false electrons to neutrons ratio is $"e"/n \simeq 10^{-2}$. If one takes into account the neutron detection efficiency including some special requirements (for each event only one neutron detector was accepted placed in the side opposite to the electron escape direction) this ratio becomes $\alpha \equiv "e"/n \sim 10^{-3}$. This estimation is confirmed by the slope of the time spectrum of the non-selected electrons.

Only the last (in time) electron signal is accepted as real. It would be enough to exclude the false electrons if the electron detection efficiency would be $\epsilon_e = 100\,\%$. However due to the different reasons (see below) this efficiency is not equal to unity. Thus the situation can occur when the real electron is not detected and the false one is interpreted as real. The presence of false electrons results in distortion of the results for λ_c and W. The cycling rate determined according to formula (3) is distorted due to the error in N_e, and W extracted from expression (4) feels the error in λ_c. More important, that the confusion of the real and false electrons leads to distortion in the relation between "sticked" series (interrupted due to the muon sticking) and "unsticked" series (ending with μ-decay). The latter are accepted more effectively. Thus the results for the muon losses are also distorted. As follows from our consideration, the error, caused by the false electron, can amount to 10% in λ_c and 20% in W. Finally, the distortion of the slope of the electron time distribution does not make it possible to correct the estimate of the D/T mixture purity, and thus to check the parameters of the purification system.

Fortunately, the cycling rate determined from the peak position in the multiplicity spectrum is free from the presence of false electrons. It is a very important circumstance allowing confident data on the cycling rate serving as a source of the "elementary" processes parameters such as the $dt\mu$-molecule formation rate. Of course, it is very desirable to obtain a correct value for λ_c by two independent methods. Moreover, to get correct data on the muon losses is an independent important task. The methods developed for this will be considered below.

2.1 Selection by the energy loss in neutron detector

The effective way to reject the false electrons was elaborated and used in our work [1]. For this we required the following when selecting events.
1. Electron signals from the WC and $ND1$ or $ND2$ should coincide.
2. Energy which electron releases in the neutron detector should be more than the maximum possible energy released by a 14 MeV neutron in this detector.
The charge spectra of one of the neutron detectors are shown in Fig. 4 for the neutrons from reactions (1), (2) and for the electrons from μ-decay.

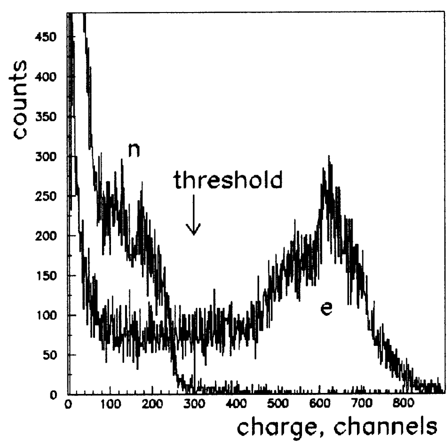

Figure 4: The charge spectra of the neutron detector for the neutrons from reactions (1), (2) and for the electrons from μ-decay in the experiment with a liquid D/T mixture.

They were measured in the experiment [1] with a liquid D/T mixture. As seen, the indicated threshold allows confident discrimination of the false electrons. The use of these selection criteria allowed us to obtain the data on λ_c and W coinciding for all three analysis methods within 5-7% [1].

The disadvantage of this selection is a decrease in the statistics because an essential part of the useful events are rejected. This decrease becomes much more sensitive in experiments with a high-pressure gaseous target having rather thick walls, for which the "output" electron energy spectra are noticeably distorted. The corresponding spectra measured with the high pressure target [2] are presented in Fig. 5. It follows from comparison of Fig. 4 and Fig. 5 that for a gaseous target reliable neutron-electron separation is connected with larger statistics losses than for a liquid target.

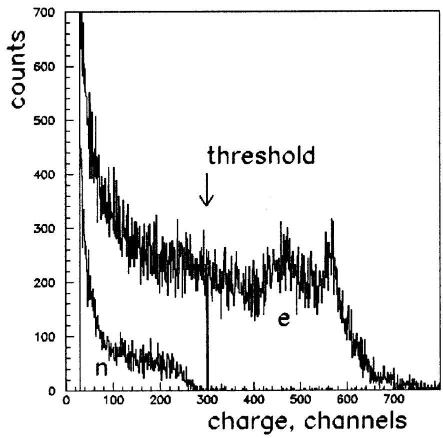

Figure 5: The same as in Fig.4 for the exposure with the gaseous D/T mixture.

This loss becomes more serious if one takes into account the finite transparency of the target walls for electrons, which is noticeably smaller for the gaseous target.

The decrease in the electron number can be estimated from the relation for the relative fraction of accepted electrons

$$f_{tot} = f_{wall} \cdot f_{\Omega} \cdot f_{sp}, \tag{5}$$

where f_{wall} is the fraction of electrons penetrating the target walls, f_{Ω} is the relative solid angle for both neutron detectors and f_{sp} is the fraction of electrons accepted after their energy selection. The values of the quantities in formula (5) are presented in Table 1 for the liquid and gaseous targets.

Table 1. The values determining the losses in the electron statistics.

	Liquid target	Gaseous target
f_{Ω}	0.6	0.6
f_{wall}	0.85	0.45
f_{sp}	0.7	0.4
f_{tot}	0.36	0.11

It follows from the data of Table 1 that the loss in statistics connected with the electron energy selection is essential, especially for the gaseous target, where only $\simeq 1/4$ of electrons penetrating the target walls is accepted. This is clearly seen in Fig. 6, where the electron time spectra are presented for two cases: with (right) and without (left) electron energy selection. That is why it is important to find the way for the false electron selection without essential loss in statistics. Of course, the use of an independent analysis method is important for the confident analysis. This method is described below.

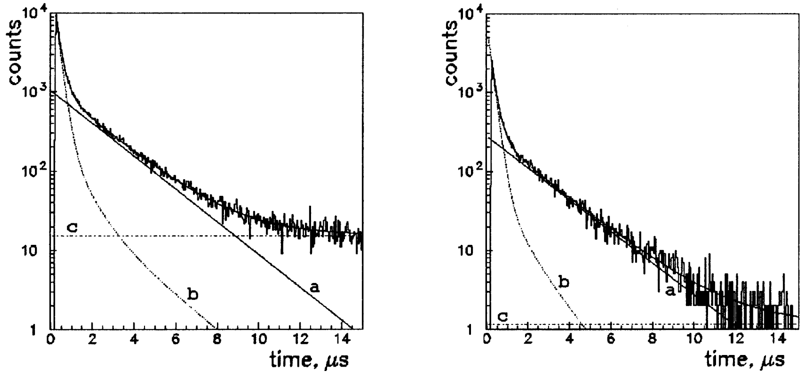

Figure 6: Electron time spectra plotted for the exposure with the D/T gaseous mixture with (right) and without (left) electron energy selection. Lines corresponds to the separated contributions from μ-decay in gas (a) and the target walls (b) and accidental background (c).

2.2 Selection by the time position of the electron signal relative to the neutron series

Now we try not to use the electron energy selection and, instead, to apply the "electron inside a neutron series" criterion. For this we consider the neutron detector charge Q (sum of amplitudes) on some time interval (ΔT) close to the electron signal and delayed relative to it by Δt (see Fig. 7). Our consideration shows that the proper values are $\Delta t = 60\,ns$ and $\Delta T = 500\,ns$. The events are accepted on condition that the charge Q is smaller than the threshold: $Q < Q_{th}$.

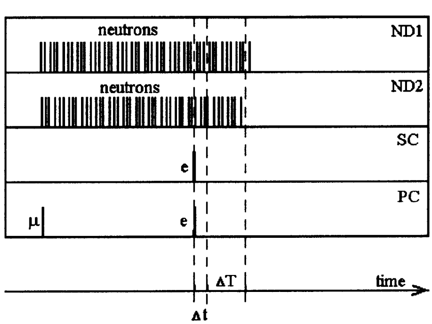

Figure 7: Criterion for the "false" electron selection.

The largest values of Q_{th} correspond to events without selection for the false electron. In this case the distortion in the electron yield and time spectrum is the largest. The opposite case (low Q_{th}) corresponds to the smallest distortions for electrons.

The efficiency of the false electron discrimination can be estimated as the Poisson probability e^{-m} to be zero neutrons on the chosen interval ΔT, where m is the mean expected number of neutrons in this interval. The number m can be expressed as $m = \beta \cdot n$, where $\beta \equiv \epsilon_n \cdot exp(-\lambda_n \Delta T)$ is the neutron detection efficiency on the interval ΔT. For the real experimental conditions $\beta \sim 0.1$. So, for the highest neutron multiplicity $n \simeq 100$ the false electron discrimination is expected to be e^{-10}. It is remarkably that we again could successfully use the high efficiency of our neutron detectors - now to eliminate the systematic errors by the most economic method.

To check our consideration and choose the optimum value of Q_{th} we investigated how the experimental results depend on the threshold charge. The dependencies of the slopes (λ_e) of the electron distribution in time

$$dN_e/dt(t) = C \cdot exp(-\lambda_e \cdot t)$$

and the neutron time distribution λ_n (4) on the threshold Q_{th} is presented in Fig. 8.

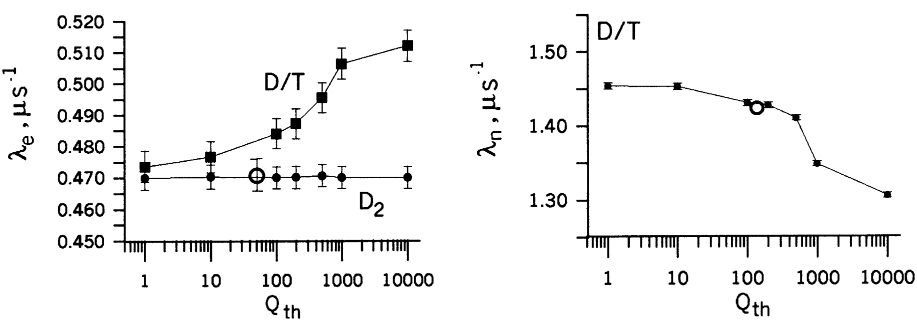

Figure 8: Dependence of the muon disappearance rate λ_e and the neutron time spectrum slope λ_n on the threshold Q_{th}. Full points correspond to the selection 'electron inside the neutron series', open circles are obtained for the electron energy selection.

As expected, the lowest Q_{th} corresponds to the minimum value of λ_e. It is pleasure to note, that the electron time spectrum slope obtained in such a manner practically coincides with the one determined with selection on the electron energy in neutron detector.

The opposite situation occurs for the slope of the neutron time distribution. When the real electron is not detected, the false one is accepted as electron. It means that the long neutron series are predominately detected because it is for those series that appearance of the false electron is most probable. Indeed, as follows from Fig. 9, the minimum Q_{th} (maximum false electron rejection) leads to the maximum slope λ_n. Again, the "correct" value of λ_n is in agreement with the one obtained with selection on the electron energy in the neutron detector.

As follows from Fig. 8, the most effective suppression of the false electrons is achieved at $Q_{th} = 10$. We chosen more 'soft' criterion $Q_{th} = 100$ to fully conserve the electron statistics. One can see from Fig. 9, that for the lowest Q_{th} some decrease in the electron number takes place. It is due to the not perfect shape of neutron detector signal having some tail.

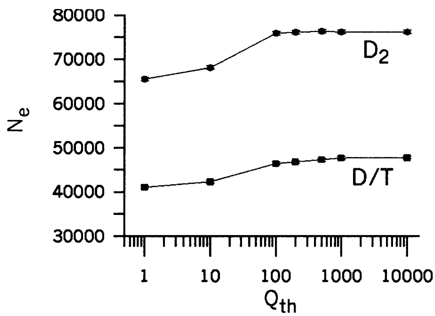

Figure 9: Total number of electrons as a function of Q_{th}.

The results obtained by the standard and multiplicity methods are presented in Table 2 for two different selection options.

Table 2. The results for the basic MCF parameters obtained for the different selection criteria.

Method for the electron selection	MCF parameters	Analysis method	
		Standard	Multiplicity
Energy loss in the *ND*	$\epsilon_n \lambda_c$	15.86 (0.24)	16.04 (0.07)
	$W \lambda_c$	0.9827 (0.0073)	0.9849 (0.0454)
Electron outside the neutron series	$\epsilon_n \lambda_c$	16.06 (0.14)	16.11 (0.07)
	$W \lambda_c$	0.9766 (0.0043)	0.9781 (0.0215)

It follows from Table 2 that the basic MCF parameters obtained with two different selection options coincide within an accuracy 3-4%. It is a rather good result if one takes into account that the total accuracy in λ_c and W is determined by the systematic ambiguity in ϵ_n consisting 5-7%. The confidence of the data is confirmed by the fact that the value of the cycling rate determined by the standard method is identical to the one found by the multiplicity method where it does not depend on the selection criteria. As follows from our consideration, the electron and neutron numbers extracted in the method considered are 4-5 times larger than in the case with energy discrimination. This is in agreement with the data of Table 1 and indicates that we could find the way for correct obtaining of the MCF parameters without essential loss in statistics.

3 Conclusion

In this article the problem of electron selection in the MCF data analysis is considered. We conclude that the selection on the electron energy released in the neutron detector allows correct determination of the MCF parameters. However, this is connected with essential electron statistics loss which becomes specially essential for measurements with a gaseous target. To avoid the statistics loss we suggest that false electrons should be discriminated by "electron outside the neutron series" criterion. This makes it possible to increase the statistics by a factor of 4-5 as comparing with the previously used method on the energy selection.

4 Acknowledgements

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Фильченков В. В. и др. E15-2002-285
О корректном определении параметров процесса мюонного катализа

Работа посвящена проблеме определения параметров процесса мюонного катализа без значительных потерь в статистике. Для этого предложен новый метод анализа, позволяющий увеличить статистику в 4–5 раз по сравнению с предыдущими методами.

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

Препринт Объединенного института ядерных исследований. Дубна, 2002

Filchenkov V. V. et al. E15-2002-285
On the Correct Determination of the MCF Parameters

This work is devoted to the problem of the determination of the MCF parameters without essential loss in statistics. A new analysis method is suggested. It makes possible to increase the statistics by a factor of 4–5 as comparing with the previous analyses.

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

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