E15-2003-199

D. L. Demin, V. V. Filchenkov, N. N. Grafov, K. I. Gritsaj,
A. D. Konin, A. I. Rudenko, S. A. Yukhimchuk,
V. G. Zinov

ON THE EXPERIMENTAL INVESTIGATION OF MUON CATALYZED $t+t$ FUSION

1 Introduction

Investigation of the muon catalyzed fusion (MCF) $t + t$ reaction

$$t + t \longrightarrow^4 He + n + n + 11.3\,MeV \tag{1}$$

is of great interest both for the full knowledge of the MCF process in the mixture of hydrogen isotopes and for the study of the reaction mechanism. It may also can give information on the properties of the nuclear system with $A = 6$.

The simplified scheme of MCF kinetics in tritium is shown in Fig. 1. The $tt\mu$ molecule

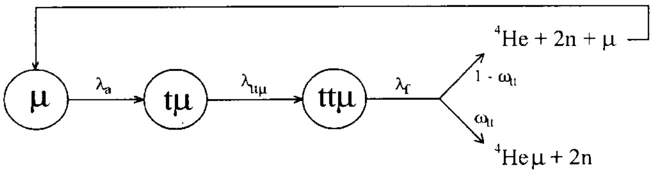

Figure 1: Diagram of MCF kinetics in tritium

is formed with the rate $\lambda_{tt\mu}$ in the $J = v = 1$ state (J and v are the rotational and vibrational quantum numbers, respectively), which gives a unique possibility of studing low-energy ($\sim 0.1\,keV$) p-wave tt fusion and properties of 1^- excited states in the lightest neutron-rich nucleus ^6He [1].

Theoretical analysis of the fusion reaction is complicated by the three-body character of the reaction (1) final state. The n and α spectra and $n - \alpha$ correlations appear to be extremely sensitive to the structure of the 1^--levels in the A=6 system [1]. The experimentally determined fusion rate gives the p-wave reaction constant, while spectra of fusion neutrons complemented by the data on the probability of the muon sticking to helium (ω_{tt}) reveal the reaction mechanism.

According to calculations [2] the values of ω_{tt} are 18%, 5% and 10% for $\alpha - n$, $n - n$ and no correlations, respectively. The neutron energy spectrum reflects the effects of the particle correlations in the final state. $n - n$-correlations result in concentration of events in the region $E_{n1} = E_{n2} = 3.8\,MeV$. For $\alpha - n$ correlations events are grouped near $E_{n1} \simeq 9.3\,MeV$ and $E_{n2} \simeq 0.5\,MeV$.

In the beam-target measurements made for $E_t = 500\,keV$ [3], the three-body breakup neutron spectrum was significantly modified by the presence of the neutron-neutron interaction and by the ^{6}He* decay via the ^{5}He ground state and via a broad ^{5}He exited state.

Contrary to other MCF processes, the $t + t$ reaction gives the continuous neutron energy spectrum whose character is poorly investigated. That is why it is hard to definitely calculate the neutron detection efficiency (ϵ_n) and, thus, to use its value in the experimental data analysis.

The way to obtain the MCF parameters without knowing ϵ_n was suggested in [4] where the value of ω_{tt} is directly determined from the ratio of measured yields of the first detected neutrons (η_1) and the second ones (η_2):

$$1 - \omega_{tt} = \eta_2/\eta_1^2\,. \tag{2}$$

However, this method involves large statistical difficulties as it requires accumulation of $\sim 10^4$ second neutrons, which is a problem at the limited value of ϵ_n. That is why the MCF parameters of the discussed process are poorly measured.

The experimental data on the main $t+t$ MCF parameters ($tt\mu$-molecule formation rate $\lambda_{tt\mu}$, fusion rate λ_f and sticking probability ω_{tt}) are summarized in Table 1 in comparison with the theoretical predictions. There are two experimental works made by PSI and

Table 1. Parameters of the tt MCF

Parameter	Source	Ref	Value
$\lambda_{tt\mu}$, $\times 10^6\, s^{-1}$	PSI experiment	[5]	1.8 ± 0.6
	RIKEN-RAL experiment	[6]	2.4 ± 0.6
	theory	[7]	2.96
	theory	[8]	2.64
λ_f, $\times 10^6\, s^{-1}$	PSI experiment	[5]	15 ± 2
	RIKEN-RAL experiment	[6]	no
	theory	[9]	13
ω_{tt}, %	PSI experiment	[5]	14 ± 3
	RIKEN-RAL experiment	[6]	8.7 ± 1.9
	theory	[9]	14

RIKEN-RAL groups. As is seen, the accuracy of most experimental values is about $20 - 30\%$ and they do not show agreement.

In the PSI experiment [5] the efficiency was $\epsilon_n \simeq 1\%$ and the authors could accumulate a few thousands of second neutrons and obtained the accuracy of about 20-30% for the MCF parameters. Another experiment was carried out by the RIKEN-RAL group [6] at the pulsed beam of the RAL accelerator. The authors determined only the slope of the "slow" component (see below) of the neutron time spectrum. To extract $\lambda_{tt\mu}$ they made rough estimation of ϵ_n and evaluated the neutron yield from the $t + t$ reaction. In both experimental works [5, 6] the evidence for the $\alpha - n$ correlations was obtained by comparing the measured recoil proton spectrum of the neutron detector with the one simulated for the absence of correlations. However, the correlations and the reaction mechanism were not analyzed.

The main feature of our suggested experiment is the use of a unique neutron detection system consisting of two high-efficiency neutron detectors placed symmetrically around the target. High ϵ_n allows high statistics, which is important for the accuracy of the MCF parameters, and, besides, makes possible an independent study of the reaction character by measuring the neutron energy spectrum and neutron angular correlations. A disadvantage of the method with high ϵ_n is noticeable pile-ups, but we are able to solve this problem.

2 Experimental method

The experimental setup is presented in Fig. 2. Incoming muons are detected by plastic scintillation counters 1,2,3 and a wire proportional counter 4 and then stop in the liquid tritium target with volume $V = 10\,cm^3$. Mu-decay electrons are detected by the wire proportional counter 5 and two plastic scintillators 1-e,2-e. Neutrons from the reaction under investigation are detected by two full-absorption detectors ND1 and ND2 ($12.5\,l$ NE-213 liquid scintillator each). Signals from the detectors are registered by six flashes

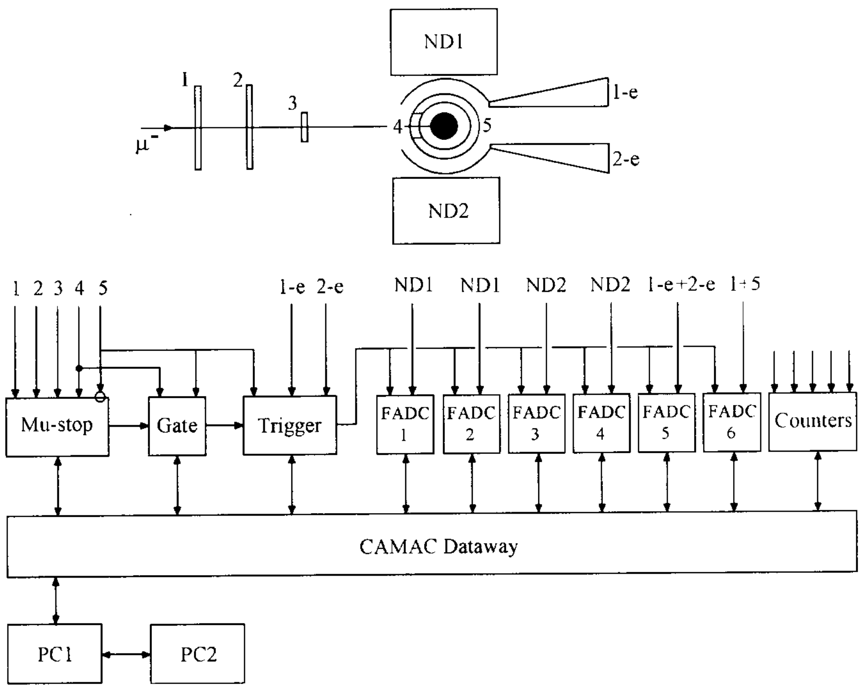

Figure 2: Scheme of the experiment

ADC (designed in Fig.2 as FADC1-6). A pair of FADC1,3 is used to read the shortened (30 ns) signals from ND's. Another pair of FADC2,4 is intended for neutron-gamma separation. For this aim each ND signal is transformed to the double signal whose parts correspond to the integral of the "fast" (50 ns) and "slow" (200 ns) components of the ND light pulse. Neutron-gamma separation is made by comparison of the "fast" and "slow" charges. The $n - \gamma$ separation makes it possible to suppress the accidental background and, especially, the background caused by the muon stops in the target walls. However, it requires $\simeq 250\,ns$. So we must introduce the responsible dead time. The possible pile-up for this time interval is checked by the FADC1,3. Finally, FADC5,6 register the signal of the muon stop and the μ-decay electron. An example of the "oscillograms" for one muon measured in the test run is shown in Fig. 3.

The test run was conducted by us with the liquid tritium target filled with $\simeq 4\ cm^3$ of liquid tritium (nuclear density $\varphi \simeq 1.3\,LHD$, $1\,LHD = 4.25 \cdot 10^{22}\,cm^{-3}$) in June 2003. In Fig.4 the time distributions of μ-decay electrons and first tt fusion neutrons are presented.

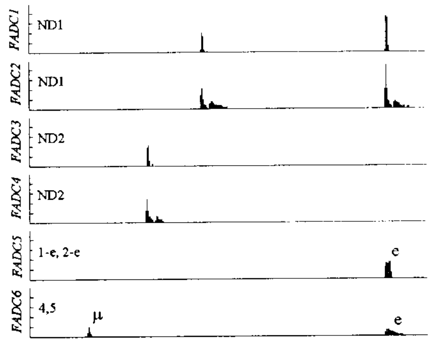

Figure 3: An example of the "oscillograms" for one muon measured in the test run.

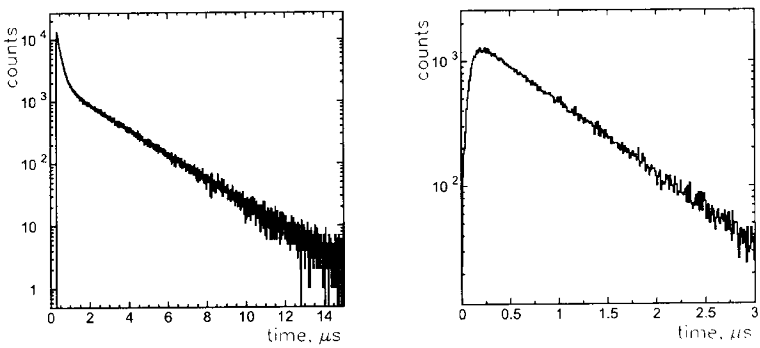

Figure 4: Time distributions of μ-decay electrons (left) and first tt fusion neutrons (right) measured in test run.

It follows from the test run that the muon stop intensity is $\simeq 4\,s^{-1}$. It means that we will have $N_\mu \simeq 1.4 \cdot 10^6$ muon stops in the 100-hour run. The absolute fusion reaction yield per muon stopped in tritium is expected to be

$$Y^0 \simeq \lambda_{tt\mu} \cdot \varphi / (\lambda_0 + \lambda_{tt\mu} \cdot \varphi \cdot \omega_{tt}) \simeq 3.$$

With the experimental yields of the first and the second detected neutrons of about

$$\eta_1 = 2 \cdot \lambda_{tt\mu} \cdot \varphi \cdot \epsilon_n / [\lambda_0 + \lambda_{tt\mu} \cdot \varphi \cdot (\epsilon_n + \omega_{tt})] \sim 0.3$$

and

$$\eta_2 = \eta_1^2 (1 - \omega_{tt}) \simeq 0.1$$

we expect to accumulate the number of second neutrons $N_n^{2-nd} = 10^4 - 10^5$. This will provide a statistical accuracy of 1% for $N_n^{2nd}/(N_n^{1st})^2 = 1 - \omega_{tt}$. The number of all detected neutrons

$$N_n = N_\mu \cdot Y^0 \cdot \epsilon_n \simeq 10^6$$

is sufficient to analyze the ND charge spectra and angular correlations between two ND to investigate the reaction mechanism.

3 Kinetics of the tt cycle

The system of differential equations corresponding to the kinetics of the processes shown in Fig. 1 is

$$dN_{t\mu}/dt = -(\lambda_0 + \lambda_{tt\mu}) \cdot N_{t\mu} + (1 - w_{tt}) \cdot \lambda_f \cdot N_{tt\mu} \tag{3}$$

$$dN_{tt\mu}/dt = -(\lambda_0 + \lambda_f) \cdot N_{tt\mu} + \lambda_{tt\mu} \cdot N_{t\mu} \tag{4}$$

with the initial conditions

$$N_{t\mu}(t = 0) = 1\,, \quad N_{tt\mu}(t = 0) = 0.$$

Here $N_{t\mu}$, $N_{tt\mu}$ are the numbers of $t\mu$-atoms and $tt\mu$ molecules; $\lambda_0 = 4.55 \cdot 10^5 s^{-1}$ is the muon decay rate. The time distribution of all neutrons N_n is

$$f(t) \equiv dN_n/dt = \lambda_f \cdot N_{tt\mu}.$$

Note that equations (3,4) (and all that follow) are written for the tritium density $\varphi = 1\,LHD$. In the case of $\varphi \neq 1\,LHD$ the collisional rate $\lambda_{tt\mu}$ must be multiplied by φ.

The exact solutions of the system of differential equations (3,4) were obtained in [4]:

$$N_{t\mu}(t) = a \cdot \frac{\lambda_0 + \lambda_f - \gamma_1}{\lambda_{tt\mu}} \cdot exp(-\gamma_1 t) + b \cdot \frac{\lambda_0 + \lambda_f - \gamma_2}{\lambda_{tt\mu}} \cdot exp(-\gamma_2 t)$$

$$N_{tt\mu}(t) = a \cdot exp(-\gamma_1 t) + b \cdot exp(-\gamma_2 t)\,,$$

where the exponential factors are

$$2\gamma_1 = \lambda_f + \lambda_{tt\mu} + 2\lambda_0 - [(\lambda_f + \lambda_{tt\mu})^2 - 4w_{tt} \cdot \lambda_f \cdot \lambda_{tt\mu})]^{1/2} \tag{5}$$

$$2\gamma_2 = \lambda_f + \lambda_{tt\mu} + 2\lambda_0 + [(\lambda_f + \lambda_{tt\mu})^2 - 4w_{tt} \cdot \lambda_f \cdot \lambda_{tt\mu})]^{1/2} \tag{6}$$

and the amplitudes are

$$a = -b = \lambda_{tt\mu}/(\gamma_2 - \gamma_1).$$

The time distribution of all detected events is

$$f(t) = A \cdot exp(-\gamma_1 t) + B \cdot exp(-\gamma_2 t), \tag{7}$$

$$A = -B = \epsilon_n \cdot \lambda_f \cdot a. \tag{8}$$

Here ϵ_n is the efficiency of registration at least one of two neutrons from reaction (1), i.e. the cycle detection efficiency. Thus the time distribution is the difference of "slow" (γ_1) and "fast" (γ_2) exponent terms with the same amplitudes.

For the first detected neutrons the system of differential equations is the same as (3,4) but in the last item of (3) the coefficient $(1 - \omega_{tt})$ must be replaced by $(1 - \omega_{tt}) \cdot (1 - \epsilon_n)$. Since $(1 - \omega_{tt}) \cdot (1 - \epsilon_n) = 1 - \epsilon_n + \omega_{tt} - \epsilon_n \cdot \omega_{tt}$, the expression for the time distribution of the first detected neutrons $f_1(t)$ is obtained by the substitution [4]

$$\omega_{tt} \to \beta \equiv \epsilon_n + \omega_{tt} - \epsilon_n \cdot \omega_{tt}.$$

Finally, the expression for the time distribution of the second detected neutrons is

$$f_2(t) = [A^2 \cdot exp(-\gamma_1 t) + B^2 \cdot exp(-\gamma_2 t)] \cdot t + \frac{2AB}{(\gamma_2 - \gamma_1)}[exp(-\gamma_1 t) - exp(-\gamma_2 t)] \tag{9}$$

with the same substitution.

4 Determination of the tt MCF parameters

4.1 General consideration

Parameters of the MCF process in tritium ($tt\mu$-molecule formation rate $\lambda_{tt\mu}$, fusion rate λ_f and sticking probability ω_{tt}) can be found from the analysis of the measured time spectra of the fusion neutrons, i.e. from the exponent slopes (5,6) and amplitudes (8).

A large neutron detection efficiency $\epsilon_n \simeq 40\%$ allows us to accumulate sufficiently high statistics $N_n^{2-nd} \sim \epsilon_n^2$ to determine ω_{tt} and, as a consequence, other parameters of the MCF in tritium, with an accuracy of $\simeq 10\%$. Such an accuracy of ω_{tt} allows the definite conclusion about the type of the correlations in the final state of the $t+t$ reaction.

Large ϵ_n results in significant difference between the time distributions of all neutrons and the first ones. It allows determining ω_{tt} from the difference of the slow component slopes of these time spectra: $\epsilon_n \cdot \lambda_c \cdot (1 - \omega_{tt})$, whereas $\epsilon_n \cdot \lambda_c$ is found from the measured neutron yield.

Even knowing ω_{tt} by using relation (2), it is a problem to obtain λ_f and $\lambda_{tt\mu}$ due to the complicated form of the expressions for the neutron time distribution. A simple way to extract each of these values was suggested in [4] by making measurements at two different densities. The sum of the slopes (5) and (6) gives the sum $\lambda_f + \lambda_{tt\mu}$, where the first value does not depend on density and the second one is proportional to it. This was used in [5] where the measurements were made for $\varphi = 1.23\,LHD$ and $\varphi = 0.022\,LHD$.

The target used in the proposed experiment is designed for operating only at one density ($\varphi \simeq 1.3\,LHD$). So, one should investigate the possibilities of determinating MCF parameters under these conditions. Another problem is the correct account of the pile-up effects. To consider the problem we have obtained appropriate expressions and made the Monte-Carlo simulations of the process.

4.2 Analysis with taking into account the dead time effects

The necessity to realize the $n-\gamma$ separation with the analysis time $\Delta t = 250$ ns requires the special selection of the detected neutrons to exclude pile-up in the indicated time interval.

The events selection scheme is as follows (see Fig.5).
1) The first neutron is accepted if the time between the first and second neutrons t_{1-2} is larger than Δt. If $t_{1-2} < \Delta t$, we reject all neutrons caused by this muon.
2) The second neutron is accepted if the time between the second and third neutrons t_{2-3} is larger than Δt and $t_{1-2} > \Delta t$. If $t_{1-2} > \Delta t$ and $t_{2-3} < \Delta t$, we accept only the first neutron from all neutrons caused by this muon.

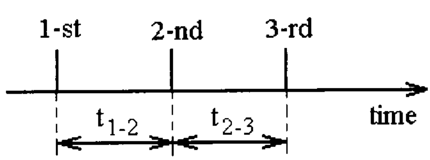

Figure 5: Neutron selection.

The dominant cause of pile-up is the high detected neutron yield under our experimental conditions. The probability that the second neutron will be in the time interval

Δt after the first one is

$$\delta = \int_0^{\Delta t} f_1(t)\, dt.$$

Taking into account the value of the neutron yield η_1 measured in the test run and the form of the neutron time distribution one should expect

$$\delta \simeq 4 - 5\,\%.$$

It is important that this value is directly measured using the short ND signals recorded in FADC1 and FADC3.

Another possible reason can be accidental background (not separated from gammas!). The corresponding value δ^c can be estimated from the total ND counting rate which was measured to be $N_{ND} \sim 10^3\, s^{-1}$. So $\delta^c = N_{ND} \cdot \Delta t < 10^{-3}$. Note that the relation between δ and δ^c is checked from the time distribution of overlapped signals.

It is more or less obvious, that the dead time selection does not change the shape of the time distribution for the first neutrons. Nevertheless, this was checked by Monte-Carlo calculations. As follows from the results of these calculations (given in Table 2) the exponent slopes of the distributions accumulated for this selection and without it coincide within an accuracy of $1 - 2\,\%$. Contrary to this, the neutron yields are changed. This leads to modification of expression (2) used for the direct determination of ω_{tt}.

Table 2. The comparison of the parameters calculated by the exact formula and those found by the Monte-Carlo code with and without dead time. The number of muons was 10^6. The values $\lambda_{tt\mu} = 3\,\mu s^{-1}$, $\lambda_f = 6\,\mu s^{-1}$, $\omega_{tt} = 0.15$, $\epsilon_n = 0.4$ were used.

Parameter	Δt, μs	By formula Eq.	By formula Value	By Monte-Carlo code
$\gamma_1, \mu s^{-1}$	0	(5)	1.574	1.576 (0.004)
$\gamma_2, \mu s^{-1}$	0	(6)	8.336	8.412 (0.047)
A	0	(8)	1.065	1.063 (0.005)
η_1	0	(7,8)	0.549	0.550 (0.001)
η_2	0	(8,9)	0.256	0.255 (0.001)
η_2/η_1^2	0	(2)	0.850	0.849 (0.012)
$\gamma_1, \mu s^{-1}$	0.3	(5)	1.574	1.573 (0.005)
$\gamma_2, \mu s^{-1}$	0.3	(6)	8.336	8.444 (0.050)
A'	0.3	(8,10)	0.941	0.937 (0.005)
η_1'	0.3	(10)	0.485	0.486 (0.001)
η_2'	0.3	(11)	0.169	0.168 (0.001)
$\eta_2'/(\eta_1')^2$	0.3	(12)	0.721	0.720 (0.011)

The yield of the first neutrons with allowance for the dead time Δt will be

$$\eta_1' = \eta_1 \cdot (1 - (1 - \omega_{tt}) \cdot \delta). \tag{10}$$

That is, the loss in η_1 connected with the dead time selection is $5 - 6\,\%$. For the second neutrons the corresponding yield is

$$\eta_2' = \eta_2 \cdot (1 - \frac{\delta}{\eta_1}) \cdot (1 - (1 - \omega_{tt}) \cdot \delta). \tag{11}$$

In this case the loss is greater and amounts to $\simeq 20\,\%$.

The first-to-second neutron yield ratio is

$$\frac{\eta_2'}{(\eta_1')^2} = (1-\omega_{tt}) \cdot \frac{1-\delta/\eta_1}{1-(1-\omega_{tt})\cdot\delta}. \tag{12}$$

So we again have an opportunity to determine ω_{tt} knowing the measured yields η_1' , η_2' and δ.

To check this calculation algorithm we carried out the Monte-Carlo simulations of tt kinetics. The resulting time distributions were fitted with formulae (7). In Table 2 the neutron yields and time distribution exponent slopes obtained by simulations and by the above formulae are compared. We have good agreement within $1-2\,\%$. The simulated time distributions are shown in Fig.6.

Finally, we attempted to analyze the parameters of the Monte-Carlo time distributions γ_1, γ_2, A', $(\eta_2'/(\eta_1')^2)$ (given in Table 2) with the aim to find the values λ_f, $\lambda_{tt\mu}$, ω_{tt} and ϵ_n as free fitting parameters. The results are presented in Table 3. As follows from Table 3, the values obtained are in good agreement with the ones taken in the Monte-Carlo simulation. It means that we are able to make full analysis even for measurements with one density.

Table 3. Comparison of the parameters obtained with the ones taken in the Monte-Carlo simulation at the dead time $\Delta t = 0.3\ \mu s$.

Parameter	Taken value	Value obtained
$\lambda_{tt\mu}, \mu s^{-1}$	3.00	2.95 (0.26)
$\lambda_f, \mu s^{-1}$	6.00	6.16 (0.27)
ω_{tt}	0.150	0.151 (0.011)
ϵ_n	0.400	0.402 (0.020)

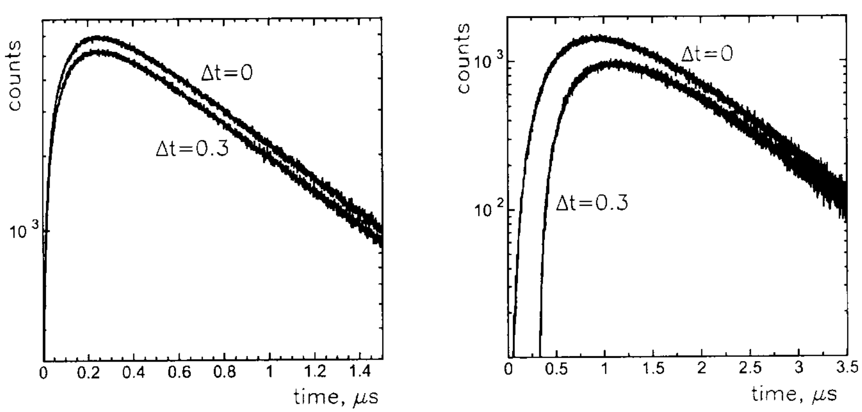

Figure 6: Simulated time distributions of first (left) and second (right) tt fusion neutrons with and without dead-time.

5 Independent information on the t+t reaction mechanism

As we mentioned the MCF parameters such as λ_f and especially ω_{tt}, give information on the $t + t$ reaction mechanism. Other important information can be obtained from the independent measurements and their analysis. These are as follows [1].

1. Analysis of the amplitude (charge) distribution of ND. Previous experiments showed that this spectrum is noticeably stronger than might be expected for the pure phase space and indicates the presence of the α - n correlations. Our neutron detection system with the large ND's has no significant advantage over smaller detectors in feeling these correlations. However, it is much more sensitive to the possible presence of n-n correlations. This can be seen from Fig.7 showing ND charge spectra simulated for three cases: no correlations, strong $\alpha - n$ and $n - n$ correlations.

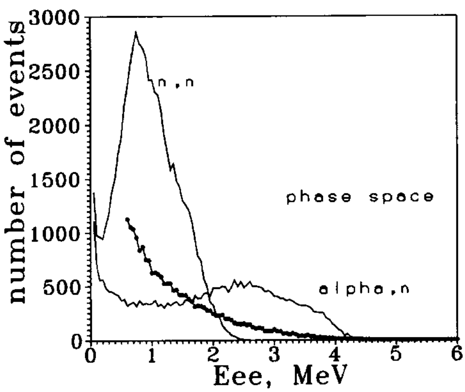

Figure 7: ND charge spectra simulated for the different assumptions of the $n - n$ and $\alpha - n$ correlations.

2. With two detectors placed in the opposite directions around the target it is possible to detect the coincidence signals between them, which would be the case of an interaction without correlation (phase space). For the pure phase space the relative part of coincidence events would be $\simeq$ 50% whereas for the $n - n$ and $\alpha - n$ correlations such events could be caused only by the rescattering effect and would not exceed 5%.

6 Conclusions

The discussed experiment based on the use of the high-efficiency neutron detection system will make it possible to substantially improve the accuracy of the MCF parameters of the $t + t$ reaction. As a result, we hope to determine ω_{tt} with the 7 – 10 % accuracy and, accordingly, to improve the accuracy of λ_f and $\lambda_{tt\mu}$ by a few times.

The best solution for the problem would be getting of self-consistent data: "without ϵ_n" (without nuclear physics) and "with ϵ_n" found on the basis of a model describing the ND energy spectrum. So MCF parameters will be obtained by two independent methods and this will allow getting reliable results both on the MCF parameters and the theoretical model of tt fusion.

References

[1] L.N. Bogdanova and V.V. Filchenkov, Hyp. Int. 138 (2001) 321.

[2] S.S. Gershtein et al., JETP 53 (1981) 872.

[3] C. Wong, J.D. Anderson, J.W. McClure, Nucl. Phys. 71 (1965) 106.

[4] V.V. Filchenkov, L.N. Somov, V.G. Zinov, NIM 228 (1984) 174; Preprint JINR, P15-82-566, Dubna, 1982.

[5] W.H. Breunlich et al., Muon Cat. Fusion 1 (1987) 121.

[6] T. Matsuzaki et al., Hyp. Int. 118 (1999) 229; T. Matsuzaki et al., Phys. Lett. B 557 (2003) 176.

[7] L.I. Ponomarev and M.P. Faifman, Zh. Eksp. Teor. Fiz. 71 (1976) 1689 (Sov. Phys. JETP 44 (1976) 886).

[8] M.P. Faifman, Muon Cat. Fusion 4 (1989) 341.

[9] L.N. Bogdanova, Muon Cat. Fusion 3 (1988) 359.

Received on October 24, 2003.

Демин Д. Л. и др. E15-2003-199
Об экспериментальном исследовании
реакции мюонного катализа $t+t$

Рассмотрен статус экспериментального исследования реакции мюонного катализа $t+t$. Обсужден планируемый эксперимент. Проведено развитие методов анализа.

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

Сообщение Объединенного института ядерных исследований. Дубна, 2003

Demin D. L. et al. E15-2003-199
On the Experimental Investigation
of Muon Catalyzed $t+t$ Fusion

The current status of the experimental investigation of muon catalyzed $t+t$ fusion is briefly considered. The proposed experiment is discussed. Analysis methods are developed.

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

Communication of the Joint Institute for Nuclear Research. Dubna, 2003

Макет *Т. Е. Попеко*

Подписано в печать 11.11.2003.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,93. Уч.-изд. л. 1,6. Тираж 280 экз. Заказ № 54176.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@pds.jinr.ru
www.jinr.ru/publish/