E15-2010-74

V. V. Baluev[1], L. N. Bogdanova[2], V. R. Bom[3], D. L. Demin,
C. W. E. van Eijk[3], V. V. Filchenkov, N. N. Grafov,
S. K. Grishechkin[1], K. I. Gritsaj, A. D. Konin,
K. L. Mikhailyukov[1], A. I. Rudenko, Yu. I. Vinogradov[1],
V. P. Volnykh, A. A. Yukhimchuk[1], S. A. Yukhimchuk

EXPERIMENTAL SEARCH FOR THE RADIATIVE CAPTURE REACTION $d + d \rightarrow {}^4\mathrm{He} + \gamma$ FROM THE $dd\mu$ MUONIC MOLECULE STATE $J = 1$

Submitted to «ЖЭТФ»

[1]Russian Federal Nuclear Center — All-Russian Scientific Research Institute of Experimental Physics (VNIIEF), Sarov, Russia
[2]State Scientific Center of Russian Federation, Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
[3]Delft University of Technology (DUT), Delft, the Netherlands

Балуев В. В. и др. E15-2010-74
Экспериментальный поиск реакции радиационного захвата $d + d \to ^4\mathrm{He} + \gamma$ из состояния $J = 1$ мюонной молекулы $dd\mu$

Для регистрации γ-квантов на установке ТРИТОН с помощью BGO-детекторов произведен поиск реакции мюонного катализа $d + d \to ^4\mathrm{He} + \gamma$ из состояния мюонной молекулы $dd\mu$. Дейтериевая мишень высокого давления экспонировалась на пучке мюонов фазотрона ОИЯИ с целью зарегистрировать γ-кванты с энергией 23,8 МэВ.

Получена экспериментальная оценка выхода реакции радиационного захвата дейтрона из состояния $J = 1$ мюонной молекулы $dd\mu$ на уровне $\eta_\gamma \leqslant 8 \cdot 10^{-7}$ в расчете на один синтез.

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

Препринт Объединенного института ядерных исследований. Дубна, 2010

Baluev V. V. et al. E15-2010-74
Experimental Search for the Radiative Capture Reaction $d + d \to ^4\mathrm{He} + \gamma$ from the $dd\mu$ Muonic Molecule State $J = 1$

A search for the muon catalyzed fusion reaction $d + d \to ^4\mathrm{He} + \gamma$ in the $dd\mu$ muonic molecule was performed using the experimental installation TRITON with BGO detectors for γ quanta. The high-pressure target filled with deuterium was exposed to the negative muon beam of the JINR Phasotron to detect γ quanta with the energy of 23.8 MeV.

An experimental estimation for the yield of radiative deuteron capture from the $dd\mu$ state $J = 1$ was obtained at a level $\eta_\gamma \leqslant 8 \cdot 10^{-7}$ per fusion.

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

Preprint of the Joint Institute for Nuclear Research. Dubna, 2010

1. INTRODUCTION

This experimental work is aimed at the observation of the rare radiative capture reaction

$$d + d \to {}^4\mathrm{He} + \gamma + 23.8 \text{ MeV} \quad (1)$$

proceeding from the $dd\mu$ muonic molecule state with the total orbital angular momentum $J = 1$. The specific feature of reaction (1) is the restricted number of partial waves. Identical bosons in the entrance channel of ${}^2\mathrm{H}(d,\gamma){}^4\mathrm{He}$ reaction select states with even $L + S$ (L and S are the orbital angular momentum and the total spin of the dd system). $E1$ radiation is forbidden to first order for two reasons. First, since $L + S$ must be even, a 1^- state requires $S = 1$, therefore the $E1$ transition would be $\Delta S = 1$. Second, the incident channel has isospin $T = 0$, hence this would be a $\Delta T = 0$, $E1$ transition which is forbidden since it violates the isospin selection rule requiring $\Delta T = \pm 1$ for $E1$ transitions in self-conjugate nuclei. This rule also implies that $\Delta T = 0$, $M2$ transitions (p-wave capture) are suppressed. $\Delta T = 0$, $M1$ transitions in self-conjugate nuclei are inhibited by about a factor of 100.

It was established in beam-target experiments that at energies $E > 400$ keV reaction (1) proceeds mainly by the quadrupole $E2$ transition from the d-wave of the deuteron relative motion to the ${}^1S_0$ state of ^{4}He [1]. At lower energies, due to barrier penetration considerations, the dominant strength should be s-wave dd capture to the D-state admixture of ^{4}He ($E2$ transition). Experiments at beam energies around 100 keV [2] support this expectation.

However, measurements of the cross section and angular distributions $\sigma(\theta)$, of the vector A_y and tensor A_{yy} analyzing powers performed with a polarized deuteron beam with energy $E_d(\mathrm{lab}) = 80$ keV stopping in the deuterium target found a p-wave involvement in the ${}^2\mathrm{H}(\vec{d},\gamma){}^4\mathrm{He}$ reaction [3,4]. It was determined that over 50% of the cross-section strength at these low energies was due to $E1$ and $M2$ p-wave captures. This finding might be considered as an isospin selection rule violation and affect the low-energy behavior of the total cross section and its extrapolation essentially to sub-Coulomb energies. It would be extremely interesting to observe a manifestation of this p wave in independent measurements.

Muon catalyzed fusion (μCF) appears to be helpful in the study of fusion reactions between hydrogen isotopes. For the dd system it allows selection of the

p-wave reactions [5]. At deuterium temperature $T \sim 300$ K, the $dd\mu$ molecule is formed by a resonance process in an excited state with total orbital angular momentum $J = 1$, and dd fusion takes place from the p wave of relative deuteron motion [5–9].

Rates of $dd\mu$ fusion reactions from this state, λ_n^f, λ_p^f,

$$dd\mu \to {}^3\mathrm{He} + n + \mu,\ {}^3\mathrm{He}\mu + n, \tag{2}$$

$$dd\mu \to t + p + \mu \tag{3}$$

were determined experimentally [8, 9]. The μCF data allowed extraction of the nuclear p-wave reaction constants and their comparison with the in-flight data R-matrix analysis results [10]. Observation of 23.8 MeV γ quanta under conditions of $dd\mu$ resonance formation, i.e., from the $J = 1$ state of the muonic molecule, would unambiguously evidence a p-wave contribution to reaction (1).

The rate λ_γ of the radiative capture reaction from the deuteron p wave

$$dd\mu \to {}^4\mathrm{He}\mu + \gamma + 23.8\ \text{MeV} \tag{4}$$

can be determined by measuring the relative yield of this reaction with respect to main channels (2), (3)

$$\eta_\gamma = \lambda_\gamma / (\lambda_n^f + \lambda_p^f). \tag{5}$$

The data [3, 4] allow a rough estimation of the expected yield $\eta_\gamma \sim (5 \div 10) \cdot 10^{-7}$ [11].

The first experimental search for reaction (1) from the $dd\mu$ molecule was undertaken in our previous measurement [12]. It resulted in the limit $\eta_\gamma < 2 \cdot 10^{-5}$. In this work we present new measurements with the use of improved methods and experimental techniques.

2. REGISTRATION OF THE CAPTURE PROCESS IN $dd\mu$ MOLECULE

The μCF process in deuterium starts when negative muons stop in liquid or gaseous deuterium. At room temperature, the rate of resonant $dd\mu$ molecule formation in the excited state $J = 1$ is [8]

$$\lambda_{dd\mu} = 3.2(3) \cdot 10^6\ \mathrm{s}^{-1} \cdot \phi, \tag{6}$$

where ϕ is deuterium density normalized to the liquid hydrogen density (LHD$=$ $4.25 \cdot 10^{22}$ n/cm^3).

Fusion reactions (2), (3) occur with the total fusion rate [9]

$$\lambda_{dd}^f = \lambda_n^f + \lambda_p^f = 407(20) \cdot 10^6\ \mathrm{s}^{-1}, \tag{7}$$

which is much higher than the free muon decay rate

$$\lambda_0 = 0.455 \cdot 10^6 \text{ s}^{-1}$$

(the muon lifetime is $\tau_\mu = 1/\lambda_0 \simeq 2.2\mu$s).

After fusion, a muon is released in most cases and can again form a $dd\mu$ molecule, starting a new cycle. The cycles stop either due to a muon decay or to its sticking to fusion products with the effective probability [9]

$$\omega_{dd} = 0.07 \pm 0.0004. \tag{8}$$

The average number of the $dd\mu$ cycles caused by one muon is estimated as

$$n_c = \frac{\lambda_{dd\mu} \cdot \phi}{\lambda_0 + \omega_{dd}\lambda_{dd\mu} \cdot \phi}. \tag{9}$$

Fusion events from reaction (4) should arrive after the muon entrance (t_μ) and before the muon decay (t_e). The idea of the experimental method consists in the delayed $\mu - \gamma - e$ coincidence registration. A signal from a delayed electron permits the timing gate for signals from the γ detectors to be registered. This diminishes the background significantly. The reaction yield is normalized to the number of muon decay electrons.

3. EXPERIMENT

The scheme of the experimental setup is shown in Fig. 1. The advancement of the setup compared to [12] was aimed at increasing the γ-quanta detection efficiency ϵ_γ and at a significant discrimination of the background [13, 14]: we made the setup as compact as possible and used novel BGO-based γ detectors which combine a high sensitivity ϵ_γ with a low efficiency to the background.

A special high-pressure deuterium target with an inner volume of 275 cm^3 was constructed at VNIIEF [15]. It was filled with deuterium gas from a dedicated source, at pressure of 575 b corresponding to a deuterium nuclear density $\phi = 0.5$ LHD at working temperature $T = 290$ K.

3.1. Detection and Registration System. Two cylinder-shaped electron detectors (*4, 5*) (one inside the other), were placed close to the target. This telescope provided a solid angle $\Omega_e \simeq 80\,\%$. Some part ($\simeq 10\,\%$) of μ-decay electrons could not pass through the target wall, so the total electron registration efficiency was

$$\epsilon_e \simeq 0.7 \tag{10}$$

with an accuracy of a few percents.

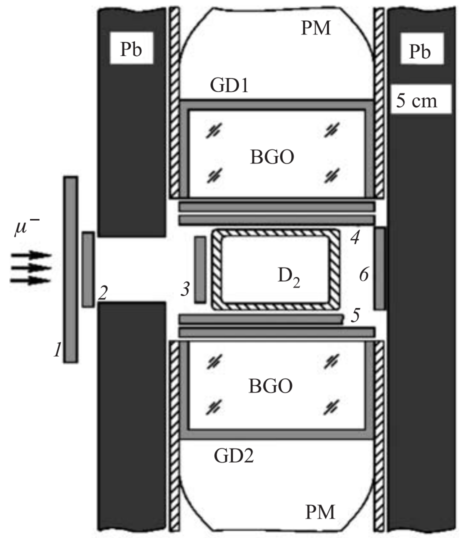

Fig. 1. Scheme of the experimental setup: *1–6* plastic counters for detection of muons coming to the D_2 target and of μ-decay electrons; GD1, GD2 — γ detectors; PM — photomultipliers

The main part of the detection system consisted of two large γ detectors — BGO crystals of 127 mm diameter and 60 mm height placed symmetrically around the target (Fig. 1). The total solid angle for both crystals was $\Omega_\gamma \simeq 40\,\%$.

The main characteristics of BGOs such as response, energy calibration and resolution, were studied at VNIIEF [16] with a ^{60}Co γ source (total energy of two γs $E_{2\gamma} = 2.5$ MeV) and an electrostatic accelerator for producing γs with energies $E_{\gamma_1} = 16.0$ MeV and $E_{\gamma_0} = 20.4$ MeV in reactions $^{11}\mathrm{B}(p,\gamma_1)^{12}\mathrm{C}^*$ (4.4 MeV) and $^{11}\mathrm{B}(p,\gamma_0)^{12}\mathrm{C}$ at the proton energy of 4.9 MeV.

It was established that the linearity of the γ detector was kept with an accuracy of $(1 \div 2)\,\%$ within the energy interval $1 \div 20$ MeV. The energy resolution function was optimized in accordance with the experimental data. For γ energies around 20 MeV it appeared to be $4\,\%$ (FWHM). The absolute efficiency of the γ detector was obtained with known cross section of the reaction $^{11}\mathrm{B}(p,\gamma)^{12}\mathrm{C}$ and the proton flux. The obtained characteristics were remarkably reproduced by GEANT-4. The response function for γs from process (4) calculated for our real experimental geometry is presented in Fig. 2. The detection efficiency turned out to be

$$\epsilon_\gamma = 15(1)\,\% \tag{11}$$

for the energy interval $20 \div 25$ MeV.

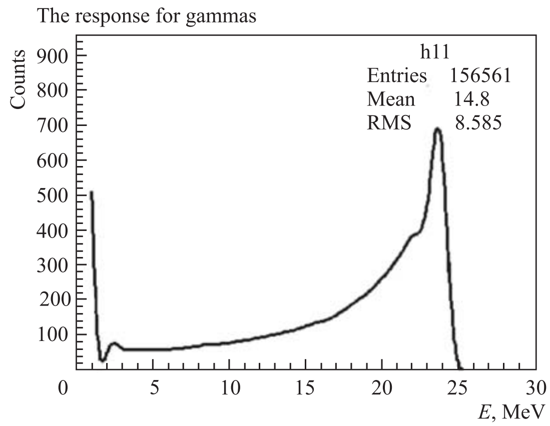

Fig. 2. Monte Carlo calculations of the response function of the γ detector for E_γ = 23.8 MeV

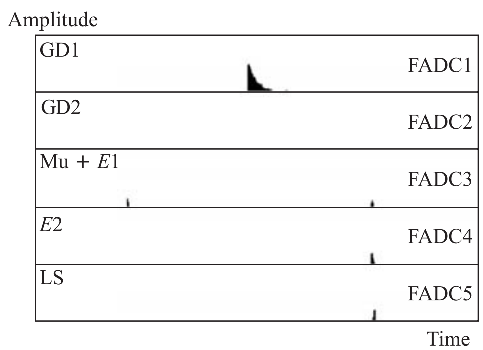

Fig. 3. Example of the «oscillogramms» — the timing of events in the registration system caused by one muon: FADC 1−5 — amplitude channels of registration system, time scale 20 μs; GD1, GD2 — signals from γ detectors; Mu+$E1$ — signals of incoming muon followed by its decay electron, $E2$ — signal of decay electron; LS — logic signals to reject accidental background

To reduce the external background, active shielding (a plastic scintillator shell of 7 mm thickness around each BGO crystal) worked in anticoincidence with BGO. Selection of the «pure» BGO signal (without plastic) was realized by comparing the charges for the fast component (30 ns) of the total signal and the slow one (300 ns). It allows decreasing of the background by one order of magnitude without a noticeable loss in the detection efficiency.

The signals from all detectors were directed to flash ADCs (8 bits$\times$ 2048 samples, 100 Mc/s). The trigger checked the presence of the muon stop signal (μ)

which was a coincidence $1, 2, 3, (\bar{4} \cdot \bar{6})$ and the electron signal $e\,(4 \cdot 5)$ in the time interval 4 μs before μ and 16 μs after it. Moreover, the absence of the second incoming muon in the indicated interval was controlled by detector 1. Under these conditions, the data from the flash ADCs were recorded in the PC memory for the further analysis. Some flash ADC signals are shown in Fig. 3.

3.2. Measurements. The D_2 target was exposed to the negative muon beam (intensity 10^4 s^{-1}, momentum 100 MeV/c) of the JINR Phasotron. The rate of muon stops in the deuterium gas resulting in μ-decay electrons was 200 s^{-1}. Additional exposure (with the empty target) was used to determine the electron background.

During the measurements we used attenuators in the amplitude channels of γ detectors. On-line calibration measurements were done with ^{60} Co γ source without an attenuator. Besides, we checked the calibration observing 5.5 MeV γs from the process $pd\mu \to^3 \mathrm{He}\mu + \gamma + 5.5$ MeV due to the presence of $0.5\,\%$ protium admixture in the target. The calibration procedure showed a good linearity (not worse than $2 \div 3\,\%$) for the energy response of the γ detector.

4. ANALYSIS OF THE EXPERIMENTAL DATA

The first step in the analysis of the registered events was the separation of μ-decay electrons $(4 \cdot 5)$ and «pure» γ quanta (presence of a signal in the BGO crystal only). Then we accumulated and analyzed the time and charge (energy deposited in the BGOs) distributions of γs. The number of μ-decay electrons necessary for normalizing the γ yield was obtained from the analysis of the electron time distribution.

4.1. Electron Time Spectra. Time spectra of electrons from muons which stopped and decayed in the target are distorted by the background originating mainly from muon decays in the target walls. In the run with the empty target, we measured the time spectra of background electrons and obtained the shape of the distribution $B_{\mathrm{empty}}(t)$. For the working exposures with deuterium-filled target, we fitted the electron time spectra taking into account the background shape:

$$N_e^{\mathrm{total}}(t) = k \cdot B_{\mathrm{empty}}(t) + A_e \cdot \exp\left(-\lambda_e t\right) + F,$$

where λ_e is the muon disappearance rate, F is an accidental background, the values k, A_e, λ_e and F are fitting parameters. The fitted time distributions of decay electrons for the deuterium-filled and empty target are shown in Fig. 4.

The muon disappearance rate $\lambda_e = 0.465(2)\ \mu\mathrm{s}^{-1}$ found from the fit appeared to be close to the free muon decay rate (7). As a result, the number of electrons from the muon decay in deuterium was obtained:

$$N_e = A_e/(\lambda_e \cdot \Delta t) \simeq 4 \cdot 10^7,$$

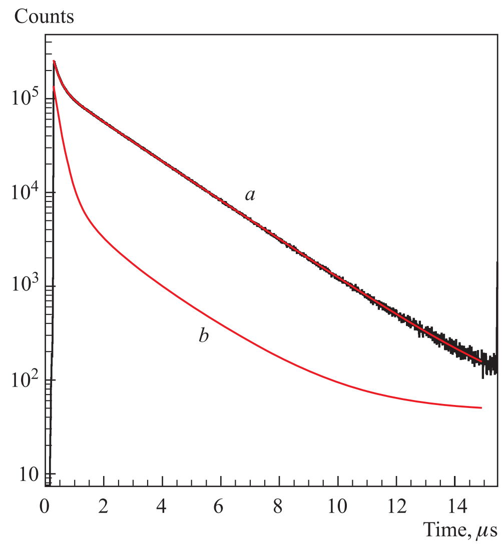

Fig. 4. Time spectra of registered electrons for the deuterium-filled target (*a*) and that for the empty target (*b*)

where $\Delta t = 20$ ns is the channel bin width. The error of N_e was determined from the uncertainty in fitting the electron time spectra from the filled and empty target and was mainly defined by the total statistics.

4.2. Selected γ Events. We analyzed charge and time distributions of the γ events selected with the use of the time criteria [12]:

$$0.5\ \mu\text{s} < t_e - t_\gamma < 2.5\ \mu\text{s};\quad 0.5\ \mu\text{s} < t_\gamma - t_\mu. \tag{12}$$

Here t_μ, t_e and t_γ are times of the muon stop, electron and γ signals, respectively. This selection allowed a radical suppression of the accidental background (by an order of magnitude). As a consequence, it also decreased the γ detection efficiency by a factor $f_t = 0.38$ ($f_t = f_{te} \cdot f_{t\mu}$, where $f_{te} = 0.48$ is due to the electron time criterion and $f_{t\mu} = 0.8$ due to the muons). The energy spectrum of events selected by this procedure is shown in Fig. 5.

For the further analysis we used the energy selection criteria

$$20\ \text{MeV} < E_\gamma < 25\ \text{MeV}. \tag{13}$$

The energy distribution for the selected interval (13) is shown in Fig. 6. We have detected $N_{\text{reg}} = 4$ events.

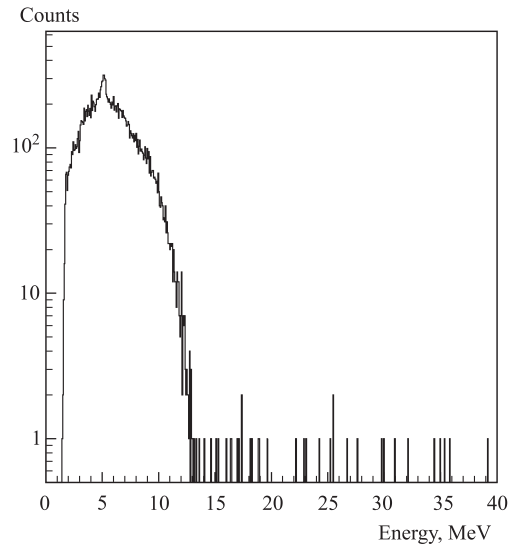

Fig. 5. Energy spectrum of γs accumulated with time criteria (12). The peak at 5.5 MeV from the pd radiative capture reaction is clearly seen

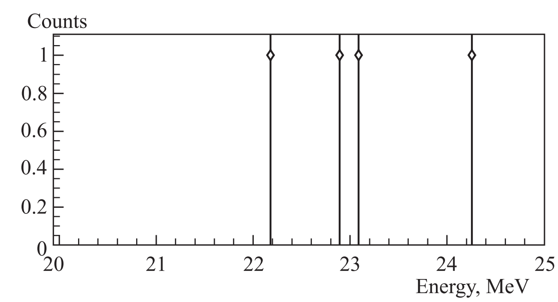

Fig. 6. The energy spectrum of the events registered in γ detectors, with the selection criteria (12), (13)

4.3. Background Estimation. There were two main sources of γ background.
1) An accidental γ followed by a real electron (muon decay in deuterium).
2) A bremsstrahlung γ (from a μ-decay electron stopped in the target wall) followed by a false e-count in the e-telescope.

To estimate the background, we analyzed the γ signals selected without electron coincidence. This gives an increase of the background events by a known factor (more than one order of magnitude).

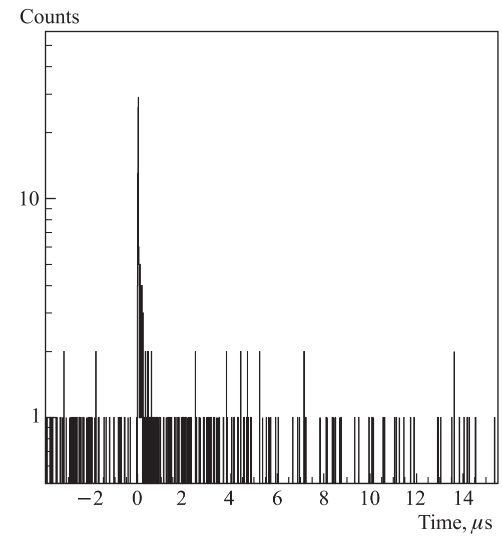

Fig. 7. The time distribution of the observed γ events for the energy interval $20 \div 25$ MeV («enhanced» background)

The time spectrum of γs selected in this way and accumulated for the energy interval (13), is presented in Fig. 7. The time-independent component is obviously due to the accidental background registered in the γ detector. From this component we derive the mean intensity $n = N/\Delta T$ of the accidental background, where N is the total number of the events in the flat component of the spectrum and ΔT is the corresponding time interval. Thus the number $N_{\rm acc}$ of accidental background events satisfying all the selection criteria, including the timing factor f_t, is

$$N_{\rm acc} \simeq n\tau_\mu f_t = 2.6. \tag{14}$$

The correlated background component, i.e., the time-dependent part of the spectrum is due to the bremsstrahlung followed by the «false» electron. The main source of the false electrons is the decay of another muon, stopped in the target before the blocking time interval (earlier than $5\,\mu$s with respect to the muon).

Electron time spectra allow one to determine the relative probabilities of the accidental electron registration $W_{\gamma-{\rm acc}}$, and of the electrons from decay of muons not blocked by a trigger, $W_{\gamma-e}$. Introducing appropriate enhancement coefficients $K_{\gamma-{\rm acc}}$ and $K_{\gamma-e}$, we can estimate the correlated background, $N_{\rm corr}$, for the selection criteria (12), (13) with the formula:

$$N_{\rm corr} = \frac{N_{\rm corr}^{\rm enh}}{W_{\gamma-{\rm acc}}K_{\gamma-{\rm acc}} + W_{\gamma-e}K_{\gamma-e}} \simeq 1.4, \qquad (15)$$

where $N_{\rm corr}^{\rm enh}$ is the number of events in the «enhanced» correlated background. The accuracy in the background estimation (15) amounts to 15%.

5. RESULTS

Basing on the estimation of the expected background $N_b = N_{\rm acc} + N_{\rm corr} = 4$ we can determine the sensitivity α of our measurements for the factual 23.8 MeV γ detection efficiency $\epsilon_\gamma \cdot f_t \simeq 0.06$:

$$\alpha = \frac{N_b/(\epsilon_\gamma \cdot f_t)}{N_e \cdot n_c} = (6 \div 8) \cdot 10^{-7}, \qquad (16)$$

where N_e is the number of the registered electrons and n_c is the average number of $dd\mu$ molecules formed per one muon. Inserting (6), (8) and $\phi = 0.5$ into formula (9) we obtain $n_c = 2.5(1)$.

With a standard algorithm, we obtain the upper limit for the relative yield η_γ (5) of reaction (4) with respect to main fusion channels (2), (3) from the $dd\mu$ state $J = 1$:

$$\eta_\gamma \leqslant 8 \cdot 10^{-7} \qquad (17)$$

at the 90% confidence level.

The upper limit for the radiative fusion rate λ_γ^1 from the $J = 1$ state of the $dd\mu$ molecule can be deduced using the experimental value of the total fusion rate (7) [8, 10]

$$\lambda_\gamma^1 < 3.5 \cdot 10^2 \ {\rm s}^{-1}.$$

6. CONCLUSION

In our previous work [12] we estimated the yield of the considered process (4) as a by-product of the main task — the measurement of the $dd\mu$-molecule formation rate [17]. The present experiment is the first serious test for investigating the possibilities of our new technique specially designed for this process. In our run we have detected $\simeq 4 \cdot 10^7$ μ-decay electrons that correspond to $\simeq 10^8$ $dd\mu$-molecule cycles. At the level of sensitivity of $\approx 7 \cdot 10^{-7}$ we have detected 4 events satisfying the selection criteria. Following the standard statistical procedure, we deduced the upper limit $8 \cdot 10^{-7}$ for the relative yield of reaction (4). This value is close to the estimations based on the data [4].

Further progress may be possible with accumulating larger statistics (by two orders of magnitude). It will allow analysis of the measured energy spectrum as the sum of two background components taken with the known weights and the signal from the studied reaction with the expected shape and variable weight.

Acknowledgements. The authors gratefully thank M. Yu. Kazarinov, A. P. Kustov, D. Mzhavia, A. G. Olchevsky, Yu. A. Polyakov, N. G. Shakun, and P. T. Shishlyannikov for support in realization of the experiment, the personnel of the JINR Phasotron and DLNP Electro-Technical Department for works on muon beam delivery. We appreciate useful discussions with C. Petitjean and L. I. Ponomarev.

This work has been supported by RFBR grants 06-02-16391-a, 08-02-01036-a, and by INTAS grant 7953.

REFERENCES

1. *Wilkinson F. J., Cecil F. E.* // Phys. Rev. C. 1985. V. 31. P. 2036.
2. *Barnes C. A. et al.* // Phys. Lett. B. 1987. V. 197. P. 315.
3. *Kramer L. H. et al.* // Phys. Lett. B. 1993. V. 304. P. 208.
4. *Sabourov K. et al.* // Phys. Rev. C. 2004. V. 70. P. 064601.
5. *Bogdanova L. N. et al.* // Phys. Lett. B. 1982. V. 115. P. 171; Erratum. B. 1986. V. 167. p. 485.
6. *Balin D. V. et al.* // Phys. Lett. B. 1984. V. 141. P. 173.; Pis'ma ZhETF 1984. V. 40. P. 318; JETP Lett. 1984. V. 40. P. 112.
7. *Balin D. V. et al.* // Muon Cat. Fusion. 1987. V. 1. P. 127.
8. *Petitjean C. et al.* // Hyp. Int. V. 118. P. 127. 1999.
9. *Voropaev N. I. et al.* // Hyp. Int. 2001. V. 138. P. 331.
10. *Hale G. M.* // Muon Cat. Fusion. 1990/1991. V. 5/6. P. 227.
11. *Bogdanova L. N., Filchenkov V. V.* // Hyp. Int. 2001. V. 138. P. 321.
12. *Bogdanova L. N. et al.* // Yad. Fiz. 2002. V. 65. P. 1826; Phys. At. Nucl. 2002. V. 65. P. 1778.
13. *Bogdanova L. N. et al.* Book of Abstracts of the 56th Intern. Conf. «Nucleus-2006», Sarov, 2006. Sarov, 2006. P. 253.
14. *Demin D. L. et al.* // Proc. of the Intern. Conf. on Muon Catalyzed Fusion and Related Topics «μCF-07», Dubna, 2007. Dubna: JINR, 2008. P. 294.
15. *Perevozchikov V. V. et al.* // Hyp. Int. 2001. V. 138. P. 417.
16. *Generalov L. N. et al.* Preprint VNIIEF. 104–2009. Sarov, 2009.
17. *Bom V. R. et al.* // ZhETF 2003. V. 123. P. 518; JETP 2003. V. 96. P. 457.

Received on June 21, 2010.

Корректор *Т. Е. Попеко*

Подписано в печать 17.08.2010.
Формат $60 \times 90/16$. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,93. Уч.-изд. л. 1,27. Тираж 290 экз. Заказ № 57074.

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