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THE YIELD OF γ QUANTA FROM THE REACTION OF NUCLEAR FUSION IN MUONIC MOLECULES $pt\mu$ AND $pd\mu$

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INTRODUCTION

To date, muon catalysis of fusion reactions in a mixture of hydrogen isotopes has been sufficiently well studied both experimentally and theoretically. The parameters of μ catalysis for the processes of *tt*, *dt*, *dd* and *pd* synthesis were measured in various experiments. The only exception is the nuclear reaction that occurs in the muonic molecule $pt\mu$ between its nuclei.

An experiment to study muon catalysis in the $pt\mu$ molecule was first proposed in [1] and carried out (in a liquid mixture of hydrogen isotopes) in the late 1980s on a PSI muon beam (Switzerland) by an international collaboration of scientists [2]. The rates of *pt* synthesis in the $pt\mu$ molecule measured in this experiment for the E0 channel significantly (up to 300 times) exceeded the theoretical calculations. This discrepancy was one of the incentives for our new experiment [3].

In our study, we chose the parameters of the liquid hydrogen mixture that are the closest to the experiment [2]. The main advantages of our experiment were the low background of γ quanta associated with the operation of the accelerator, the use of two γ detectors, and the high efficiency of registration of the reaction products of the muon catalysis cycle.

The study of the following synthesis channels in *pt* muonic molecule has been carried out:

$$pt\mu \to {}^4\mathrm{He}\mu + \gamma, \tag{1}$$

$$pt\mu \to {}^4\mathrm{He}\mu + \gamma + \gamma, \tag{2}$$

$$pt\mu \to {}^4\mathrm{He} + \mu_{\mathrm{conv}}, \tag{3}$$

$$pt\mu \to {}^4\mathrm{He}\mu + e^+ + e^-, \tag{4}$$

where the fusion energy $E \approx 19.8$ MeV. In addition, the following channels of the nuclear *pd* reaction in the $pd\mu$ molecule were studied:

$$pd\mu \to {}^3\mathrm{He}\mu + \gamma, \tag{5}$$

$$pd\mu \to {}^3\mathrm{He}\mu + \gamma + \gamma, \tag{6}$$

for which the fusion energy $E \approx 5.5$ MeV.

Note that reaction channels (1) and (3) were observed earlier in a single experiment [2] to study the reactions of muon catalysis in the muonic molecule $pt\mu$. Reactions (2) and (4) were not observed, including in beam experiments. Only in the course of these experimental studies with the participation of a muon was it possible for the first time to observe reaction channels (2), (4), and (6). Reaction (1) with the liberated muon was also observed. This paper presents a study of reaction channels (1), (2) and (5), (6) with the yield of γ quanta.

1. EXPERIMENT

The experiment was carried out at the Triton facility [4], located on the negative muon beam of the Phasotron of the Dzhelepov Laboratory of Nuclear Problems of JINR. A beam with a momentum of 100 MeV/c and an intensity of 10^4 s^{-1} was used. The scheme of the experiment is shown in Fig. 1.

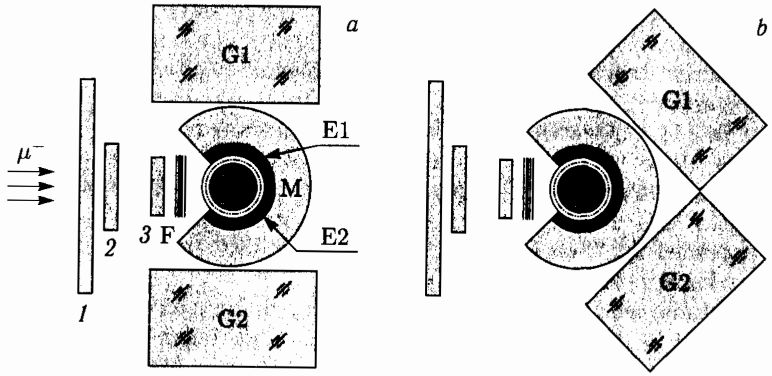

Fig. 1. Scheme of the experiment: *a*) for exposures I, II, IV; *b*) for exposure III; *1–3* — muon beam counters, F — copper muon moderator, H/T — target, E1, E2 — electron detectors, *M* — muon detector, G1, G2 — γ-ray detectors

For the experiment, a target with a working volume of 50 cm^3 was made [5]. The target was filled with liquid hydrogen at a temperature of 22 K with a small content of heavy hydrogen isotopes. To register γ quanta, we used the same γ detectors G1 and G2 based on bismuth germanate (BGO) crystals, which were used in the experiment [6]. Electrons from the decay of muons in the target and e^+e^- pairs from reaction (4) were recorded by electron detectors E1 and E2. Conversion muons from reaction (3) were recorded by a muon detector *M*, the thickness of which was chosen from the condition of guaranteed stopping of the conversion muon in the detector body. The experimental technique and data processing are described in detail in [3].

During the experiment, the oscillograms of events were recorded from detectors G1, G2, E1, E2, *M* and counter *3* of the muon beam. An example of such an oscillogram is shown in Fig. 2. Four exposures were performed: three with tritium (two concentrations of tritium and two angles of γ detectors) and one with hydrogen. In all exposures, the deuterium content was close to the natural concentration of deuterium. Exposure parameters are summarized in Table 1.

Table 1. **Exposure parameters: c_t and c_d — content of tritium and deuterium, α — angle between γ detectors, N_μ — number of muons stopped in the target**

Exposure	c_t, % [5]	c_d, %	α, deg	N_μ
I	0.84 ± 0.01	0.023 ± 0.01	180	10^7
II	0.1 ± 0.01	0.016 ± 0.01	180	10^7
III	0.1 ± 0.01	0.016 ± 0.01	110	10^7
IV	0	0.011–0.016 [7]	180	10^6

2. OBSERVATION OF DOUBLE γ QUANTA

In Fig. 2, an oscillogram is shown of the experimental event of muon catalysis corresponding to reaction (2), which was observed for the first time.

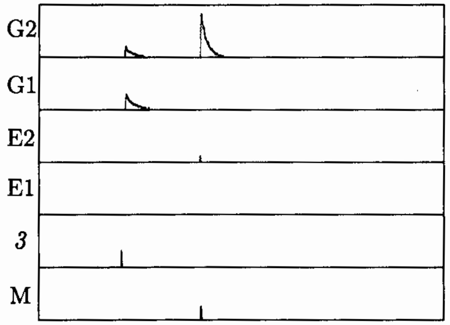

Fig. 2. Oscillogram of an experimental event with the release of a pair of γ quanta from reaction (2). The counts in the detectors are shown in accordance with the designations in Fig. 1. The scale of the figure in time is 20 μs

The first signal in time is the stop of the muon in the target (counting in counter *3*), the second group of signals (G1, G2) is the registration of γ quanta simultaneously in two γ detectors, the third group of signals (*M*, E2, G2) is the registration of one and the same electron from the muon decay reaction in the target ($\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$). For reaction (6), the oscillogram of the event is similar, the difference lies in the sum of the energies of two γ quanta.

The total energy spectrum for two γ detectors is shown in Fig. 3. Here, panel *a* demonstrates the spectrum corresponding to reactions (2) and (6), which was observed in exposures II + III, panel *b* corresponds only to reaction (6), since there was no tritium in exposure IV.

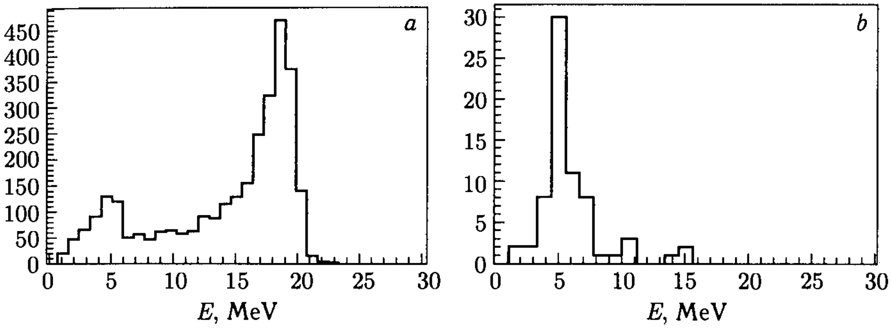

Fig. 3. Total experimental energy spectrum of double γ quanta: *a*) exposures II + III; *b*) exposure IV

The total energy spectrum for exposure I (similar to the spectrum shown in Fig. 3, *a*) contains γ quanta from both reaction (2) (peak 19.8 MeV) and reaction (6) (peak 5.5 MeV), which proceeds due to the presence of an impurity of deuterium. The latter circumstance made it possible to determine the percentage of the yields of double γ quanta in reaction channels (2) and (6) for exposures I and II (Table 2). Exposure III was excluded from consideration because of the large contribution of the rescattering of γ quanta from reaction (5), due to the relative position of detectors G1 and G2. In addition, it was not possible to determine the rate of the nuclear transition in reaction (6) due to insufficient statistics.

The experimental energy spectrum of one γ quantum from reaction (2) (the energy spectrum of the registered γ quanta in one of the γ detectors (G1 or G2) in the presence of a counting in the other) and the corresponding model theoretical spectrum are shown in Fig. 4. They are in good qualitative agreement, given that the wings of the experimental distribution contain rescattering events (which made the greatest contribution to exposure III, where the γ detectors were approximated). To determine the rate of the nuclear transition in reaction (2), γ quanta were selected from the central region of this spectrum in order to reduce the systematic error. The peak in the region of 1 MeV is due to the rescattering of single γ quanta from one γ detector to another (from G1 to G2 and vice versa).

The model spectrum shown in Fig. 4 is a theoretical distribution that follows from the assumption of a two-photon E0 transition between the levels of the nuclear ^{4}He* system upon its deexcitation to the ground state. Such a $0 \to 0$ transition mechanism is well known in atomic physics (for example, $2S^{1/2} \to 1S^{1/2}$ in the hydrogen atom, which plays an important role in the evolution of the hot Universe). This distribution has the form $x^3(E-x)^3$, where x is the energy of one γ quantum from a pair, and E is the transition energy (in our case, $E \approx 19.8$ MeV), and the maximum of the distribution corresponds to the energy value $E/2$.

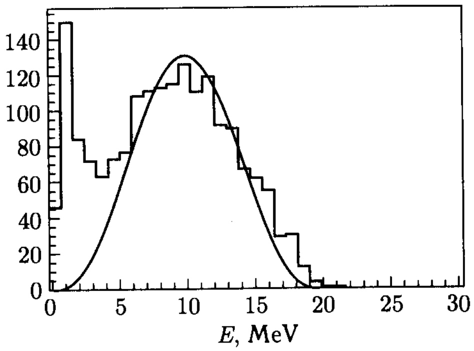

Fig. 4. Experimental (histogram) and model (solid line) energy spectra of one of two γ quanta from reaction (2) (exposure III)

In order to study the dependence of the yield of γ quanta on the angle of their emission in reaction (2), exposures II and III were carried out with different positions of γ detectors relative to the target. No significant dependence of the yield of γ quanta on the emission angle was found in reaction (2).

3. OBSERVATION OF SINGLE γ QUANTA

The discovery of new channels for the synthesis of nuclei of muonic molecules with the release of two γ quanta (2) and (6) contributed to the elucidation of the reason for the distortion of the experimental spectra in the previous study [2]: having only one γ detector, the experimenters could not separate the channel with double γ quanta and recorded them as belonging to reaction channel (1) with the output of a single γ quantum. For example, Fig. 5 shows how the experimental energy spectrum of single γ quanta is distorted if only one γ quantum from a pair is recorded from the reaction channel with the release of two γ quanta at a high relative yield in this reaction channel (2). In fact, the experimental spectrum of single γ quanta consists of the following γ quanta:

- from reaction channels (1), (2), (5);
- 1.6-MeV peak — from the cascade emission of muons intercepted by heavier atoms of the target walls, into which the mesoatoms diffuse;
- 2.2-MeV peak — from radiative neutron capture by hydrogen in the target;
- from the typical response of a BGO crystal to fast neutrons [8].

Note that the source of the time-correlated neutron background is fusion reactions in muonic molecules $dd\mu$ and $dt\mu$, which, along with $pt\mu$, are also formed in the target when the muon from the beam stops there, but despite the low concentration of heavy isotopes in hydrogen and due to the high velocity of their formation with the subsequent emission of neutrons noticeably distort the left wing of the experimental spectrum of single γ quanta.

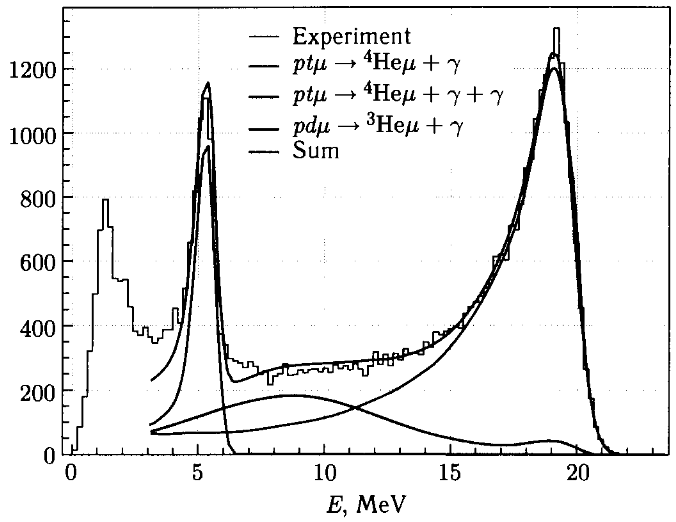

Fig. 5. Energy spectrum of single γ quanta for exposure I: histogram — experimental spectrum; blue, green, black lines — simulation of the response of the γ detector for reaction channels (1), (2), (5), respectively, red line — total simulated response

The relative yields (Table 2) for reaction channels (1), (2), (5), and (6) were determined by fitting the experimental spectrum with the function of the total simulated response of the detector, taking into account the calculated efficiencies. The calculation of the registration efficiency ε was carried out by the Monte Carlo method using the GEANT4 program.

Table 2. **Efficiency of registration ε and experimental relative yield in reaction channels for exposures I and II. The error in determining the relative yields does not exceed 15%**

Reaction channel	ε, %	Relative yields, %	
		Exposure I	Exposure II
Double γ quanta			
$(pd\mu \to {}^3\mathrm{He}\mu + \gamma + \gamma)/(pt\mu \to {}^4\mathrm{He}\mu + \gamma + \gamma)$	0.94/1.43	7.6	13.4
Single γ quanta			
$pt\mu \to {}^4\mathrm{He}\mu + \gamma$	11.7	67.3	28.7
$pt\mu \to {}^4\mathrm{He}\mu + \gamma + \gamma$ (one of a pair)	18.2	14.3	7.4
$pd\mu \to {}^3\mathrm{He}\mu + \gamma$	10.2	18.4	63.9

In each exposure with tritium, it was possible to register several tens of sequential single γ quanta. An example of an oscillogram of such an event (using the designations from Fig. 1) is shown in Fig. 6.

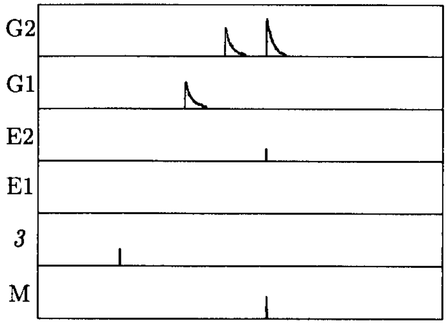

Fig. 6. Oscillogram of an experimental event with the release of two successive γ quanta. The scale of the figure in time is 20 μs

Similar events were also observed in exposure IV. This made it possible to estimate the partial (related to the yield in the reaction channel with a single γ quantum) coefficient of muon sticking [9] to radiogenic helium ω_s during synthesis in muonic molecules $pt\mu$ and by recording successive events of muon catalysis [10]. The obtained values are presented in Table 3 and are close to theoretical estimates [11]. The same table shows the absolute yields of γ quanta Y^0 of the corresponding reactions.

Table 3. **Absolute yields Y^0, reaction rates λ, and partial sticking coefficient ω_s**

Reaction channel	Physical quantity	Value	Exposure
$pt\mu \to {}^4\mathrm{He}\mu + \gamma$	λ^{γ}_{pt}, $\mu\mathrm{s}^{-1}$	0.078(4)	I
	Y^0 (γ), %	3.28(5)	I
	Y^0 (γ), %	2.47(5)	II
	Y^0 (γ), %	2.55(25)	III
	ω_s, %	0.991(1)	I
$pt\mu \to {}^4\mathrm{He}\mu + \gamma + \gamma$	$\lambda^{2\gamma}_{pt}$, $\mu\mathrm{s}^{-1}$	0.15(6)	I
	$\lambda^{2\gamma}_{pt}$, $\mu\mathrm{s}^{-1}$	0.14(5)	II, III
	Y^0 (2γ), %	1.61(6)	I
	Y^0 (2γ), %	1.44(6)	II
	Y^0 (2γ), %	1.51(16)	III
$pd\mu \to {}^3\mathrm{He}\mu + \gamma$	λ^{γ}_{pd}, $\mu\mathrm{s}^{-1}$	0.25(4)	IV
	Y^0 (γ), %	15.3(2.3)	IV
	ω_s, %	0.994(1)	IV
$pd\mu \to {}^3\mathrm{He}\mu + \gamma + \gamma$	Y^0 (2γ), %	0.5(0.1)	IV

4. RESULTS AND DISCUSSION

Data processing of the experiment, the results of which are presented in Table 3, was carried out according to the method described in detail in [3].

The main systematic errors arose in the selection of single γ quanta against the background of binary ones and in the opposite case.

The absolute yields $Y^0(y)$ of reaction products y were calculated by the formula $Y^0(y) = N_y/(N_\mu \varepsilon(y) f_t)$, where N_y is the number of registered reaction products, N_μ is the number of muons stopped in the target, $\varepsilon(y)$ is the detection efficiency, and $f_t = 0.668$ is the time factor arising from the imposed condition $0.5 \leqslant t(y) - t(e) \leqslant 4.5$, where $t(y)$ and $t(e)$ are the times of registration of the reaction product and electron from muon decay in microseconds. As the number of muons stopped in the target, we took the number of registered electrons under the condition $t(e) - t(\mu) \geqslant 0.5$ μs, where $t(\mu)$ is the time of the muon stop in the target. The efficiency of registration of muon catalysis products was obtained by simulating physical processes in the target and detectors using the GEANT4 program.

The nuclear reaction rate λ^y was determined by fitting the time spectrum of the corresponding reaction channel.

The partial sticking coefficient ω_s was calculated by the formula $1 - \omega_s = N_{\gamma\,\mathrm{seq}}/(N_\gamma \varepsilon(\gamma))$, where $N_{\gamma\,\mathrm{seq}}$ is the number of registered events with the release of two successive γ quanta (Fig. 6).

SUMMARY

The main result of this work is the first observation of double γ quanta in the output channel of the pt-fusion reaction proceeding in the muonic $pt\mu$ molecule. The reliability of such an event is confirmed by the agreement between experiment and theory (two-photon E0 transition), as well as the obtained rate $\lambda_{pt}^{2\gamma}$, which, within the error limits, coincides with the rate of the E0 transition measured in [2].

The yield in reaction channel (2) remained at the same level with decreasing tritium concentration, which follows from the calculations of the kinetics of muon catalysis (Fig. 13 from [4]) and coincides with similar calculations from [2].

It should be added that earlier in experiment [6], about a hundred events were observed that met the selection criteria for γ quanta having energy in accordance with the final state of fusion reaction (1) with the yield of single γ quanta. It can be assumed that this process occurs not in the muonic $pt\mu$ molecule, but "in flight", when the "hot" muonic tritium atom from the reaction $dd\mu \to t\mu + p$ collides with the HD molecule in the atmosphere of dense deuterium. There is no other explanation for this fact at the moment. Note also that in the data of the same experiment [6], we failed to distinguish events corresponding to the reaction $dd\mu \to {}^4\mathrm{He}\mu + 2\gamma$.

The preliminary results of the experiment were presented at the International Conference NTIHEP-18 [12]. The processing of the obtained experimental data required for a detailed description of channels (3) and (4) is currently continuing.

The studies carried out in this work show the possibility of measuring the yield of reaction (6) even with the natural content of deuterium in hydrogen.

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