EXPERIMENTAL ANALYSIS OF MUON CATALYZED FUSION KINETICS IN TRIPLE MIXTURE OF HYDROGEN ISOTOPES

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Since the discovery of resonant formation of $dd\mu$ and $dt\mu$ molecules in 1977 [1], main experiments in MCF — measurements of total neutron yields and determination of formation rates of muonic molecules, were performed in mixtures of deuterium and tritium in gaseous, liquid and solid phases [2]. An new direction of research was opened by our experiments [3] at PSI on direct measurement of muon sticking probability ω_{dt} in triple H/D/T mixture, where the new epithermal mechanism of $dt\mu$ catalysis was discovered. In the media with large concentration of hydrogen ($C_p \approx 90\%$) the $t\mu$ atoms, formed via exchange of muons from protons and deuterons, pertain high kinetic energy in the range near 1 eV for considerably long time due to low cross-section of scattering on hydrogen (Ramsauer effect). In this energy range there is a maximum of $dt\mu$ molecule formation, which is estimated [4] to be $\lambda_{dt\mu-hD} = 10^{10}$ s^{-1}. This feature raises hope to obtain greater total yield of neutrons of dt fusion, expressed as $Y_n \sim \lambda_c/(\lambda_0 + \tilde{\omega}_{dt}\lambda_c)$. Here λ_c is the measured cycling rate of $dt\mu$ fusion, and $\tilde{\omega}_{dt}$ is the effective probability of muon sticking, accounting for all losses. We can see that at fixed $\tilde{\omega}_{dt}$, the yield is proportional to the cycling rate, which depends on the parameters of triple mixture.

The main problem in the description of MCF kinetics in H/D/T mixture is to take into account the energy of $d\mu$ and $t\mu$ atoms after muon exchange and during thermalization, this requires knowledge of muonic atoms scattering cross-sections in the ground state and in excited states [5]. In this analysis the $t\mu$ atoms were split into 3 energy groups: "fast" — with energy above 0.6 eV, "epithermal" — with energies in the interval 0.2–0.6 eV, around the resonance of $dt\mu$ formation, and the third — thermalized $t\mu$ atoms with energy 0.04 eV. The kinetic diagram of MCF in this approach is shown in Fig.1. Another approximation is the merging of two muon exchange processes, $p\mu \rightarrow d\mu \rightarrow t\mu$ and $p\mu \rightarrow t\mu$ into one process $p\mu \rightarrow t\mu$ with effective yield $W = (\lambda_{pt}/\lambda_{pd})^{eff}\ (C_t/C_d)$. We evaluate only the ratio $(\lambda_{pt}/\lambda_{pd})^{eff}$ by fitting the time spectra, not using theoretical values of the exchange rates, unlike considered in the analysis of [5]. We used the data of the experiment at PSI [3] together with the data of the first experiment at LNPI, Gatchina [6], with high concentration of tritium, as specified in Table 1.

Table 1

Experiment	C_p,%	C_d,%	C_t,%	Density (LHD)	Yield of fusions,%	Pileups,%
LNPI-85a	88.4	8.9	2.68	0.087	13.3(7)	14.4(7)
LNPI-85b	75.6	21.6	2.75	0.085	16.7(8)	16.3(8)
PSI-89	90.5	9.5	0.047	0.168	2.15(15)	0.62(4)

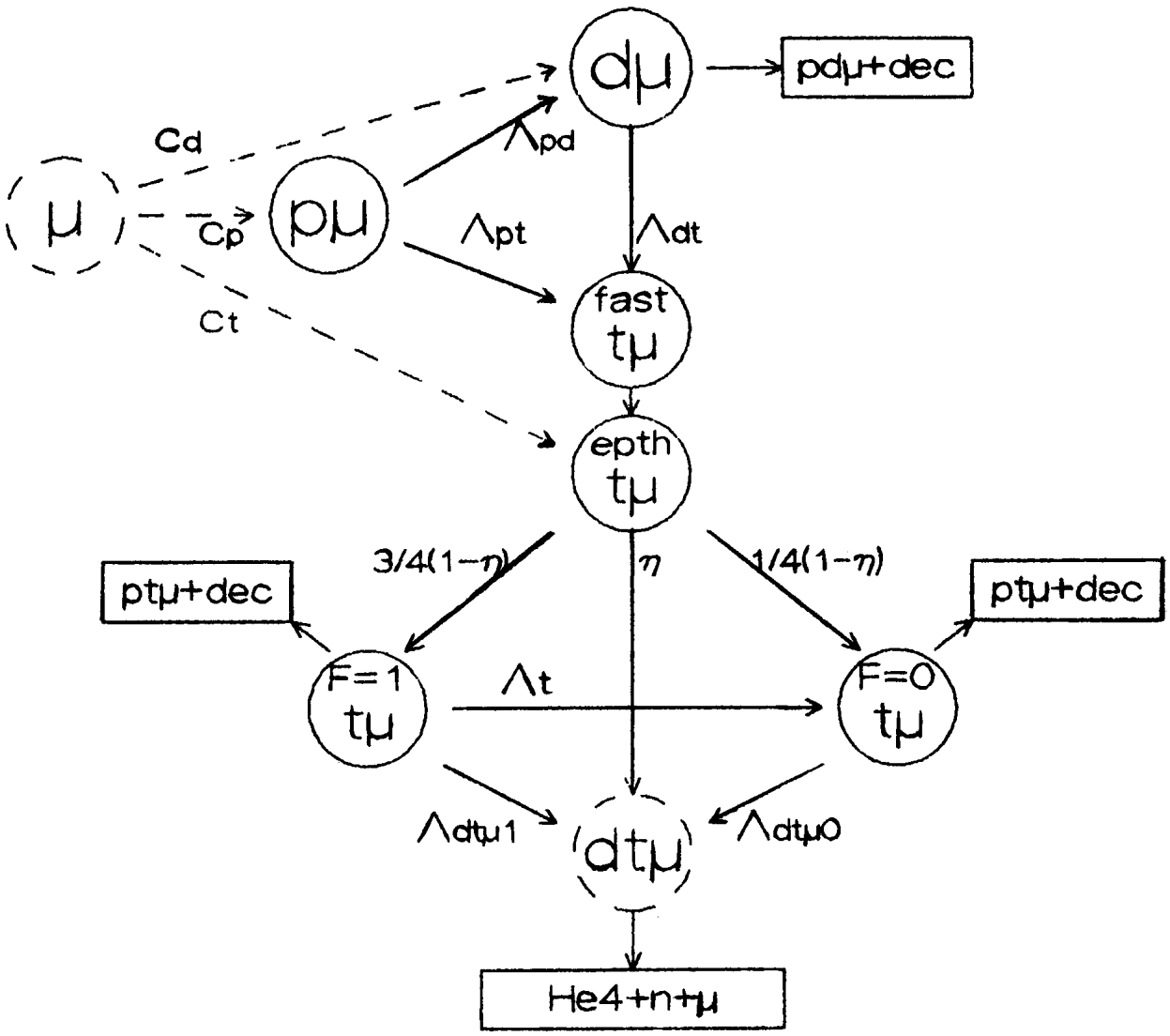

Fig.1. Kinetic diagram of muon catalyzed fusion in a triple mixture of hydrogen isotopes. Node "fast" is $t\mu$ atoms with energy above 0.6 eV. Node "epth" denotes $t\mu$ atoms with energies in interval of resonant $dt\mu$ formation, $0.2-0.6$ eV, η is probability of epithermal $dt\mu$ formation

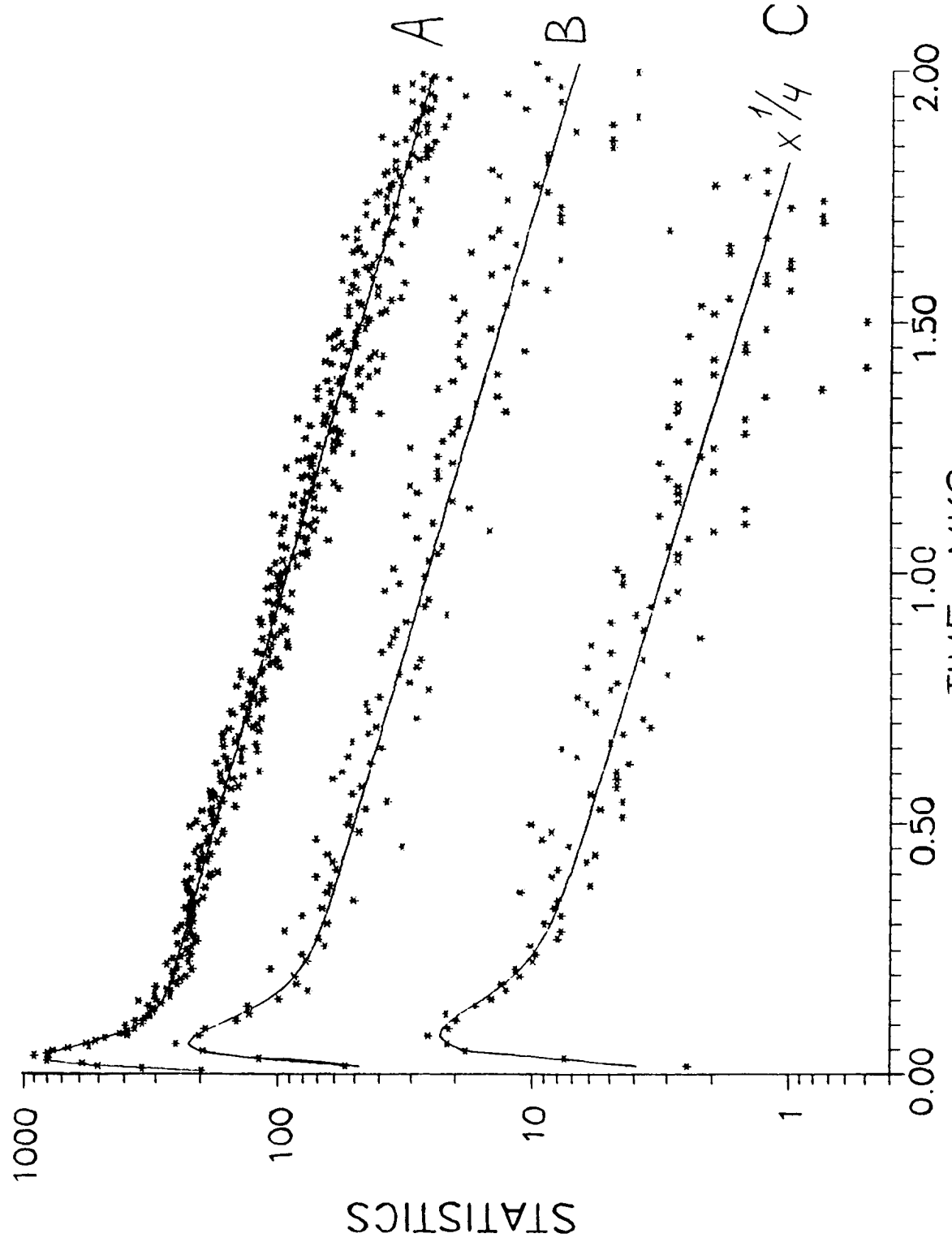

Fig. 2. Experimental time spectra of dt-fusion neutrons in PSI-89 (a), -91 (b), -92 (c) experiments, and curves of fitting with respect to LNPI-85 data

The fast processes manifested themselves in $\alpha - \alpha$ pileups, their number was observed in the energy spectrum of α-particles of dt fusion in the IC. The evaluated rates of processes expressed in units of 10^6 s^{-1} at LND and the probability of epithermal formation of $dt\mu$ molecules η are listed in Table 2. The time spectra of dt-fusion neutrons with fitting curves are shown in Fig.2.

Table 2

$\lambda_{pd\mu}$	λ_{dt}	$\lambda_{dt\mu}(F=0)$	$\lambda_{dt\mu}(F=1)$	$(\lambda_{pt}/\lambda_{pd})^{eff}$	η ,%
5.6 ± 0.1	341 ± 20	20 ± 10	120 ± 25	2.4 ± 0.5	22 ± 5

The most interesting results of this analysis are the values of catalysis rates on the molecules HD from the two spin states of $t\mu$ atoms, $F = 0$ and $F = 1$. Their values are approximately 3 times lower than expected by the theory [4]. but their difference is the same as predicted. Taking into account the spin states leads to another value of muon transfer rate λ_{dt}. In our approximation the rate of epithermal formation is found to be $\lambda_{dt\mu-HD} = (2500 \pm 600) \cdot 10^6$ s^{-1}, more than one order of magnitude higher than for thermalized $t\mu$ atoms. The contribution of this process in our experimental conditions is $\approx 1/4$ of the total yield. It is interesting to note that the ratio of exchange rates $(\lambda_{pt}/\lambda_{pd})^{eff}$ that has effect on description of the epithermal peak, is unexpectedly high. This can possibly mean lower value of λ_{pd} than the theoretically predicted one, keeping in mind that such experimental estimates also exist [7].

The obtained results are the first approximation to description of complicated MCF processes in triple mixtures of hydrogen isotopes.

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