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THE INVESTIGATION OF THE PARAMETERS OF MUON CATALYZED FUSION IN DOUBLE D/T MIXTURE AT HIGH TEMPERATURE AND DENSITY

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1 Introduction

The muon catalyzed (MC) fusion is an interesting and unique process having neutron yield of nuclear fusion reactions dependent on the macroscopic parameters of a medium (temperature, density, medium content). MC is characterized by originality of physical processes and so the investigation of MC itself represents the independent scientific interest. The investigation of MC processes serves the solution of fundamental three body problem with coulomb interaction with relativistic corrections.

The present work is the prolongation of a wide experimental program of thorough study of the muon catalyzed processes. The conditions of the current investigation are located in a region (high temperatures and density) most sensitive in the check of the theoretical predictions. In present the reliable data in this region of temperature and density are absent.

This study is being conducted using TRITON installation placed on muon channel of LNP phasotron. In the scope of the program two experimental runs were performed in 1999y. The aim of the experiment was the measurement of the "effective" parameters (cycling rate λ_c, neutron yield Y_n, muon loss w) of muon catalyzed processes in double D/T mixture of hydrogen isotopes with respect to tritium concentration in the mixture at temperatures 300, 550 and 800 K and densities 0.3, 0.4, 0.5 and 0.6 LHD of that of liquid hydrogen density (1 $LHD = 4.25 \cdot 10^{22} nuclei/cm^3$). The present experiment was performed in a more wide range of temperature, density and tritium concentration as compared to our previous experiment with similar parameters of D/T mixture [1]. It is worth mentioning that the region of high pressures was not studied intensively by far. Nevertheless the new channels of $dt\mu$-molecule formation found in this region would give rise to the progress in the theory.

2 The experimental setup and the experimental conditions

The experimental setup used in performing the investigation is described in the reference [1]. The Tritium High Pressure Target [2] with the working volume 16.5 cm^3 is the central part of the installation. The gas handling was provided by the Gas Mix Preparation System [3]. The detectors of the installation are described in [1,4]. The experimental method is analogous to that found in [5]. The conditions of the exposures (together with the values λ_c and w obtained) can be seen in the Table 1. The duration of the exposures (getting proper statistics of the experimental events) was equal $7 - 10$ h. The monitoring of the molecular composition of the mixtures was done with the aid of a chromatography. The analysis showed equilibrium (high temperature) molecular compositions for each mixture exposed to a muon beam.

3 Analysis

The preliminary data treatment has been done analyzing the time distributions of "all" neutrons and electrons, as well as the neutron "multiplicity" distribution. As a result of the data handling the values of λ_c, w and Y_n have been obtained for 33 exposures with double D/T mixture. The analysis was done using "standard method" and the "multiplicity method", those methods are described in the work [5]. The discrepancy in the value of λ_c received using those different methods is $5-10$ %. As a resulting values for λ_c we take those received with the "multiplicity method". The values include the improvement due to the neutron pile-up effect [6], resulting in the increase of neutron detection efficiency. The determination of the neutron detection efficiency (in our experiment we use neutron detectors of large volume) is properly elaborated in the work [7]. In present experiment we had the efficiency to neutrons $\simeq 22\%$.

4 Results

In present time the data handling process is not finished. In this work we give the preliminary values of cycling rate, effective muon losses and neutron yield in the MC fusion cycle. They are presented in the Table 1 and in the Fig.1,2. One can see the cycle rate temperature dependencies measured at different mixture (D/T) density and tritium concentration in the Fig.1. Fig.2 shows obtained values of neutron yield with respect to tritium concentration in double mixture at different temperature and density. The experimental errors in the depicted values of cycling rate, muon losses and neutron multiplicity amount to $5-8\%$.

The dependencies of the cycling rate on the tritium concentration found in the experiment with double D/T mixture at different densities and temperatures were analyzed in "steady state" condition using the following expression [8]:

$$\frac{1}{\lambda_c} = \frac{q_{1s} C_d}{\lambda_{dt} C_t} + \frac{1}{(\lambda_{dt\mu-d} C_{DD} + \lambda_{dt\mu-t} C_{DT})}, \tag{1}$$

here C_d - deuterium isotope concentration in D/T mixture,
C_t - tritium isotope concentration in D/T mixture,
C_{DD} - molecular concentration D_2 in D/T mixture,
C_{DT} - molecular concentration DT in D/T mixture,
q_{1s} - probability that $d\mu$-atom approaches the 1-s state,
$\lambda_{dt\mu-d}$, $\lambda_{dt\mu-t}$, - formation rate of $dt\mu$-molecules via molecules D_2 and DT,
λ_{dt} - muon transfer rate $d\mu$-$t\mu$.

For the value of q_{1s} (C_t) the following expression was chosen:

$$q_{1s}(C_t) = 1/(1 + a \cdot C_t).$$

The following values was used as "free" parameters defined in the fit procedure: a, $\lambda_{dt\mu-d}$ and values $\lambda_{dt\mu-t}$ at three temperatures $(300, 550$ and $800\ K)$.

The values of the kinetics parameters used in the fit and the parameters to define are summarized in the Table 2. The validity of the expression used has been proved with the Monte-Carlo simulations and the calculations of the MC kinetics.

We conduct three fit procedures (binding cycling rate and tritium concentration) for three sets of exposures with same densities of D/T mixture (0.3, 0.4 and 0.5 LHD). Analyzing the dependence λ_c (C_t) we consider the values q_{1s} and $\lambda_{dt\mu-d}$ constant in the temperature region 300 – 800 K).

The fit (expression 1) results in values q_{1s}, $\lambda_{dt\mu-d}$ and $\lambda_{dt\mu-t}$ at three temperatures (300, 550 and 800 K).

The results of the analysis of dependence $\lambda_c(C_t)$ are depicted in the Figs.3-6.

The experimental dependence $\lambda_c(C_T)$ at 0.3 LHD mixture density is shown in the Fig.3, the optimum fit is shown with the curve. The optimum fits have analogous look for different mixture densities.

The dependence $\lambda_{dt\mu-d}$ vs. density is shown in the Fig.4.

The dependence of the values of $\lambda_{dt\mu-t}$, received from the fit vs. temperature at three different densities of D/T mixture is shown in the Fig.5. The curves represent theoretical imagination of the dependence $\lambda_{dt\mu-t}$. The results of the analysis of $\lambda_c(C_t)$ for the exposures with mixture density 0.5 LHD are shown together with the results of the work [9].

The values of q_{1s} resulting from the fit are shown in the Fig.6 in comparison with the results [10].

5 Conclusion

The values of the MC cycling rates are in agreement with those received in our previous work [1]. Analyzing the results of the dependence of cycling rates on the tritium concentration one should conclude that the theoretical values of resonant mesomolecule formation rate [10] are in severe excess over the experiment. This coincides with the conclusions made in the work [11].

In the future we would improve the analysis choosing sound models for the cascade stage of μ-atoms and for the character of changing the $dt\mu$-molecule formation rates with temperature.

To conduct a more thorough analysis one should take additional measurements in double D/T mixture at high tritium concentrations (up to 90%). For this purpose it is necessary to create a new tritium target able to operate at high tritium concentrations. Seems to be important the analysis of the time distributions of the first detected neutrons with the aim of the determination of the ratio of the formation rates from different initial states of $t\mu$-atom.

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Table 1: The experimental conditions of the exposures and the experimental values of cycling rate λ_c and effective muon losses w. The values of λ_c are normalized on mixture density

RUN	Press., bar	Temp., K	Isotope concentrations, %			Density, LHD	λ_C, μs^{-1}	w, %
			Cp	Cd	Ct			
T04	460(20)	300(10)	0.8(0.1)	30.7(0.3)	68.5(0.5)	0.411(0.016)	50.5	1.2
T05	780(30)	550(10)	same	same	same	0.385(0.016)	103.5	1.0
T06	1050(40)	800(10)	same	same	same	0.368(0.016)	142.5	1.3
T07	320(20)	300(10)	0.7(0.1)	30.5(0.3)	68.8(0.5)	0.310(0.012)	48.2	1.4
T08	550(20)	550(10)	same	same	same	0.289(0.012)	105.2	1.0
T09	750(30)	800(10)	same	same	same	0.273(0.012)	142.2	1.2
T10	650(30)	300(10)	0.7(0.1)	46.5(0.5)	52.8(0.5)	0.532(0.021)	89.6	1.0
T11	1100(40)	550(10)	same	same	same	0.502(0.021)	133.9	0.85
T12	1400(40)	550(10)	0.6(0.1)	47.9(0.5)	51.5(0.5)	0.604(0.024)	132.2	0.89
T13	1600(40)	635(10)	same	same	same	0.597(0.024)	141.3	0.92
T17	1500(40)	800(10)	same	same	same	0.491(0.021)	156.9	1.1
T19	1150(40)	800(10)	same	same	same	0.397(0.016)	162.9	1.1
T20	320(20)	300(10)	0.5(0.1)	47.5(0.5)	52.0(0.5)	0.310(0.012)	77.2	1.3
T22	540(20)	550(10)	same	same	same	0.283(0.012)	142.8	1.1
T23	750(30)	800(10)	same	same	same	0.273(0.012)	169.0	1.1
T27	630(30)	300(10)	0.9(0.1)	64.9(0.5)	35.2(0.3)	0.518(0.021)	106.2	1.3
T28	1050(40)	550(10)	same	same	same	0.490(0.021)	128.1	1.2
T29	1470(40)	800(10)	same	same	same	0.484(0.021)	139.8	1.3
T30	1050(40)	800(10)	same	same	same	0.375(0.016)	154.9	1.4
T31	300(20)	300(10)	0.4(0.1)	63.5(0.5)	36.1(0.3)	0.295(0.012)	101.8	1.1
T40	520(20)	550(10)	same	same	same	0.280(0.012)	137.2	1.1
T42	730(30)	800(10)	same	same	same	0.268(0.012)	156.0	1.2
T44	290(20)	300(10)	0.4(0.1)	81.7(0.5)	17.9(0.2)	0.300(0.012)	69.2	2.2
T45	550(20)	550(10)	same	same	same	0.289(0.012)	80.3	1.9
T46	750(30)	800(10)	same	same	same	0.273(0.012)	78.8	2.1
T48	630(30)	300(10)	0.2(0.1)	81.6(0.5)	18.2(0.2)	0.515(0.021)	73.1	2.0
T49	1120(40)	550(10)	same	same	same	0.505(0.021)	78.5	1.8
T51	1470(40)	800(10)	same	same	same	0.484(0.021)	70.0	1.8
T52	1160(40)	800(10)	same	same	same	0.400(0.016)	86.5	1.9
T55	460(20)	300(10)	0.4(0.1)	51.9(1.0)	47.7(1.0)	0.409(0.020)	90.1	0.91
T56	770(20)	550(10)	same	same	same	0.383(0.020)	135.2	0.84
T57	480(20)	300(10)	0.3(0.1)	67.0(1.0)	32.7(1.0)	0.425(0.020)	101.6	0.88
T58	810(20)	550(10)	same	same	same	0.399(0.020)	128.8	0.94
T65	480(20)	300(10)	0.4(0.1)	84.2(1.0)	15.4(0.5)	0.434(0.020)	57.9	0.91
T68	830(20)	550(10)	same	same	same	0.407(0.020)	66.8	0.85
T72	1400(40)	300(10)	0.1(0.1)	98.5(1.0)	1.4(0.3)	0.859(0.040)	5.0	7.6

Table 2: The parameters of MC kinetics used in the fit and the values to define

Parameter	Symbol	Value (μs^{-1})
Probability that $d\mu$-atom approaches the basic state	q_{1s}	fit
Muon transfer rate $d\mu - t\mu$	λ_{dt}	280
$dt\mu$-molecule formation rate	$\lambda_{dt\mu-d}$	fit
	$\lambda_{dt\mu-t}$	fit

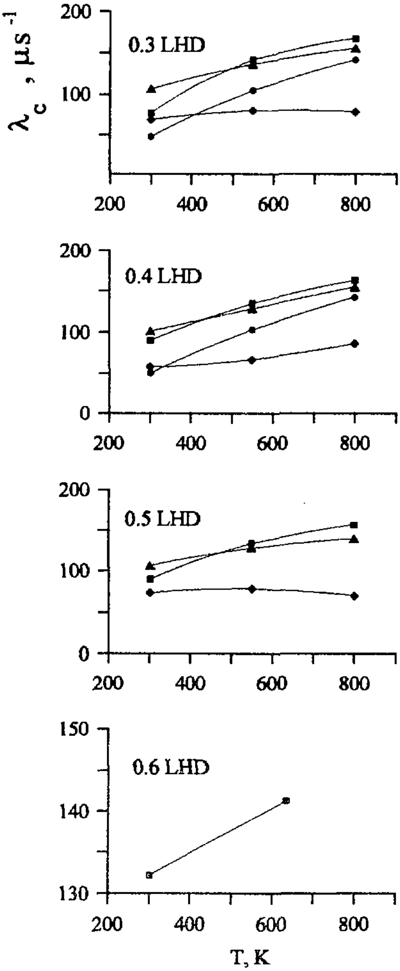

Figure 1: The dependencies of cycling rate λ_c on temperature of the mixture at four different densities ($0.3, 0.4, 0.5$ and 0.6 LHD) and at four tritium concentrations ($18\%, 35\%, 52\%, 68\%$). The values of λ_c have been normalized to liquid hydrogen density. Experimental points: circles - $C_t = 68\%$; squares - $C_t = 52\%$; triangles - $C_t = 35\%$; rhombuses - $C_t = 18\%$. The curves are drawn to connect the points having same tritium concentration

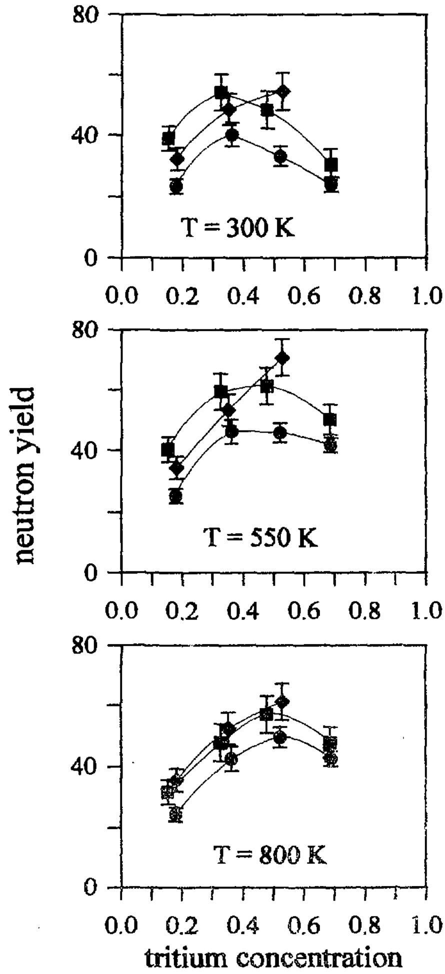

Figure 2: The values of neutron yield obtained in experiment with respect to tritium concentration at three values of temperature and three values of mixture density. Experimental points shown in figure are: circles - at density 0.3 LHD; squares - at density 0.4 LHD; rhombuses - at density 0.5 LHD. The curves are drawn to connect the points having same mixture density

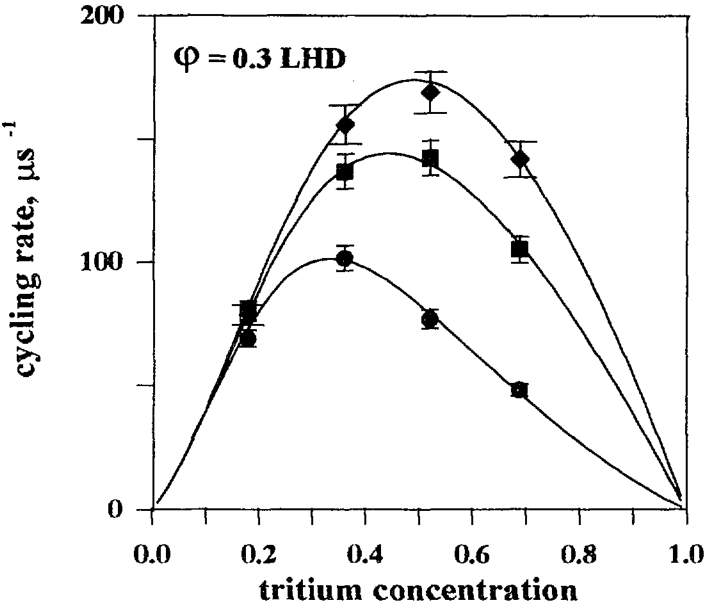

Figure 3: The dependencies of cycling rate λ_c on tritium concentration measured at three temperatures and at relative density $\phi = 0.3\,LHD$. The values of λ_c have been normalized to liquid hydrogen density. Experimental points: rhombuses - $T = 800\,K$; squares - $T = 550\,K$; and circles - $T = 300\,K$. The line represents the fit with optimal values of mesomolecule formation rates $\lambda_{dt\mu-d,t}$

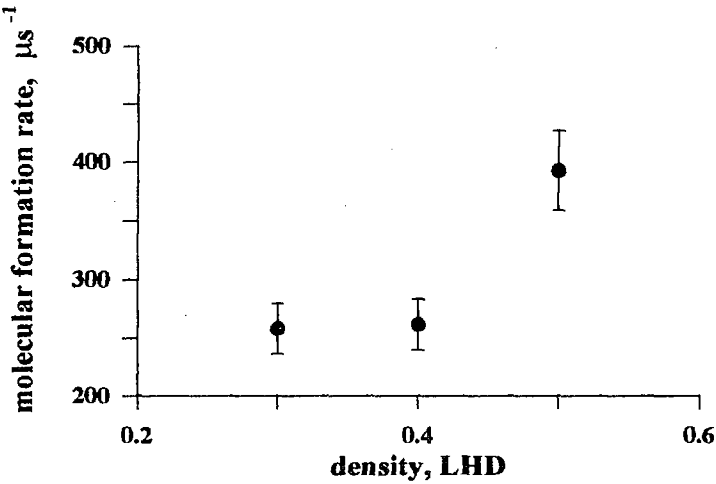

Figure 4: The dependence of the formation rate $\lambda_{dt\mu-d}$ of mesomolecules $dt\mu$ via the molecule D_2 with the respect to the density of D/T mixture. We take the value of $\lambda_{dt\mu-d}$ to be constant in the temperature range $T = 300 - 800\,K$

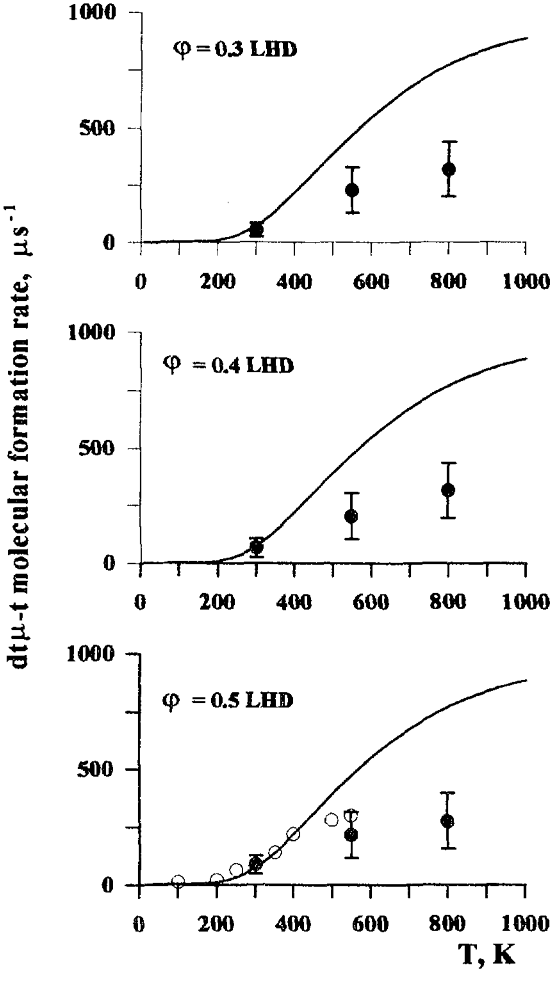

Figure 5: The dependence of the formation rates $\lambda_{dt\mu-t}$ of $dt\mu$-molecules via the molecule DT with the respect to temperature. This dependence is obtained on the basis of the measurements at density $\phi = 0.3$ using the expression 1. Points - the values of $\lambda_{dt\mu-t}$ received from the fit, lines - theoretical expectations [10] empty circles - result of the work [9]

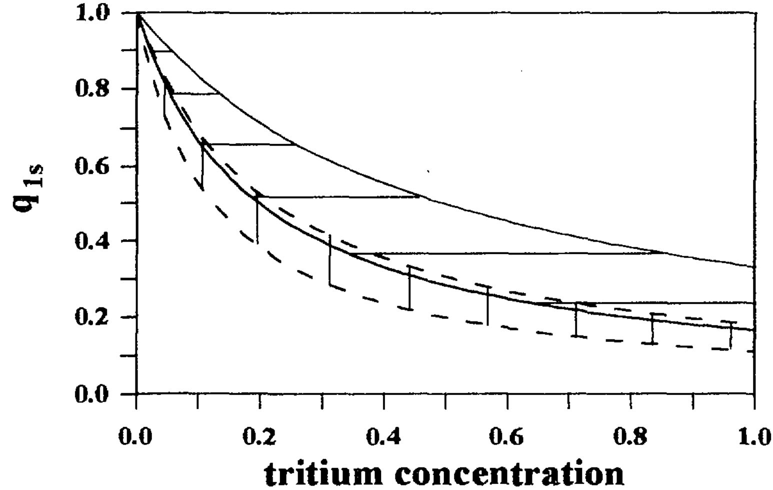

Figure 6: The value of q_{1s} obtained in the fit in comparison with the results of the work [10]. The horizontal shading - the region of the values of q_{1s} as follows from the work [10], the vertical shading - the region of the values of q_{1s} obtained from the fit of our experimental parameters

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