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STATUS OF THE INVESTIGATION
OF THE MUON CATALYZED $d+t$ REACTION

1 Introduction

Now that the great experimental material on the MCF has been accumulated due to the efforts of many groups, it is important to sum up all data and to decide on the direction of further study. It is especially desirable in view of the fact that the most serious reviews on this subject were published more than ten years ago [1, 2, 3].

The simplified scheme of the processes caused by negative muons in a D/T mixture is shown in Fig. 1.
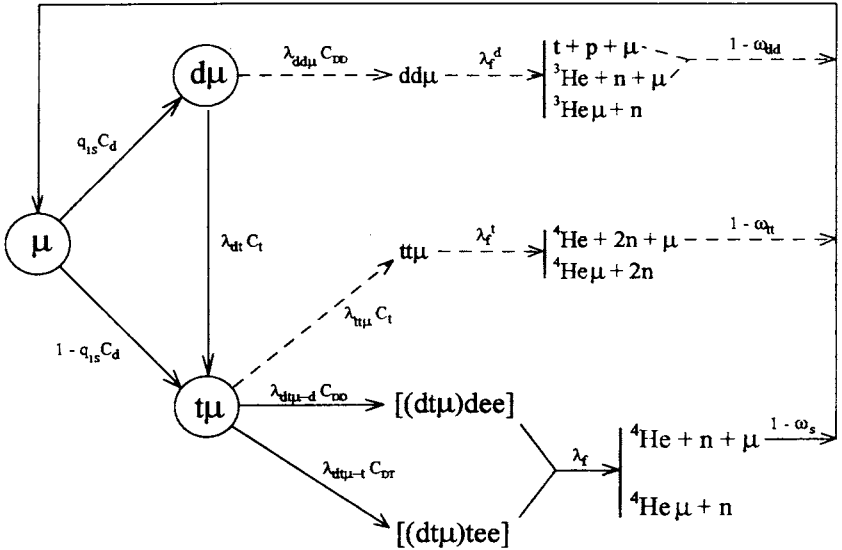

Figure 1: The simplified scheme of the MCF processes in a D/T mixture.

Stopping in the mixture muons form $t\mu$- or $d\mu$-atoms in their ground states with the probabilities $w_{t\mu} = C_t + C_d \cdot (1 - q_{1S})$ and $w_{d\mu} = C_d \cdot q_{1S}$ respectively, where C_t and C_d are relative hydrogen isotope concentrations and q_{1S} takes into account the muon transfer from $d\mu$ to $t\mu$ during the deexcitation cascade [4]. According to the theory q_{1S} must strongly depend on the mixture density and tritium concentration.

The "standard" cascade model, in which initial μ-atom energies are distributed around $E_0 = (1-2)\,eV$, is apparently valid only at very low densities $\varphi \le 10^{-3}\,LHD$ (φ is relative to the liquid hydrogen density $LHD = 4.25 \cdot 10^{22}\,cm^{-3}$). Now it is known that during the cascade muonic atoms can be both thermalyzed and accelerated getting the energy of even tens of eV (see, for example, [5, 6, 7]). However, till now the problem of knowing the initial energy distribution of muonic atoms after the cascade is not solved definitely.

Being in the $d\mu$-atom ground state, the muon can be transferred to tritium in the collisional process

$$d\mu + t \longrightarrow t\mu + d \qquad (1)$$

with the rate $\lambda_{dt} = 2.8 \cdot 10^8 \, s^{-1} \cdot \varphi$ [8, 9, 10, 11]. In transfer process (1) the $t\mu$-atom acquires the energy 19 eV.

Muonic atoms $t\mu$ can form $dt\mu$ and $tt\mu$ molecules and $d\mu$ atoms can form $dd\mu$-molecules. The fusion reactions can occur in these mu-molecules in which the muon can be released and stimulate the next MCF cycle or stick to helium produced in the reactions. The appropriate notations for the rates of muonic formation and fusion reactions as well as for the sticking probabilities are indicated in Fig. 1. Being bound in the mu-atom or mu-molecule or being free, the muon disappears with the rate $\lambda_0 = 4.55 \cdot 10^5 \, s^{-1}$.

The specific feature of the $dd\mu$- and $dt\mu$-molecule formation processes is their resonance character, that is, the muonic molecular formation rates $\lambda_{dd\mu}$ and $\lambda_{dt\mu}$ turn out to depend on the mu-atom kinetic energy [3]. The MCF $d + d$ cycle has been studied very well. The measured temperature dependence $\lambda_{dd\mu}(T)$ is in excellent agreement with theory. Its analysis allows the precise determination of the binding energy of the level $J = v = 1$ (J, v are the rotational and vibration quantum numbers) and the fusion reaction rate

$$E_{J=v=1} = 1964.83 \, meV, \qquad \lambda_f^{dd}(J=1) = 405^{+20}_{-15} \cdot 10^8 \, s^{-1} \, .$$

Quite a different situation takes place for the MCF $d+t$ cycle. Really, this process has been studied in detail in that parameter region (low temperatures) where the "standard" theory predicts its relatively low intensity. It follows from experiment that just in this region the MCF process turns out to be very effective. Modern theory explains this only qualitatively. On the other hand, the first attempts to penetrate into the high temperature region, where the "standard" theory predicts the highest intensity of the MCF process, indicate its lower intensity. Below this will be considered in more detail.

2 "Standard" theory prediction

It follows from the original Vesman consideration [12, 3] that the resonance $dt\mu$-molecule formation occurs in the interaction of the $t\mu$-atom with D_2, DT or HD molecules according to the scheme

$$t\mu + (DX)_{K_i} \longrightarrow [(dt\mu), x, 2e]_{v,K_f} \quad X = H, D, T \quad x = p, d, t, \qquad (2)$$
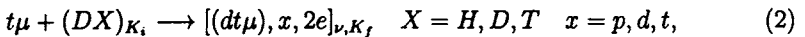
where the energy released under $dt\mu$ formation together with the $t\mu$-atom kinetic energy $E_{t\mu}$ is transferred to excite the vibration-rotational state of the molecular complex $[(dt\mu), x, 2e]$. Here K_i and K_f are the rotational quantum numbers of the

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"initial" molecule DX and the "final" complex respectively. The set of the resonance $t\mu$-atom energies

$$E_{t\mu}^\tau = \Delta E_{\nu,K}$$

corresponds to different transitions $\nu = 3, 4, 5$; $K_i \rightarrow K_f$. Really, the spin states of the $t\mu$-atom and the $dt\mu$-molecule should be taken into account for determination of $E_{t\mu}^\tau$. In addition, the position and intensity of the resonances depend on the type of molecule (D_2, DT and HD) and the temperature of the mixture influencing the population of the rotational states of these molecules.

The resonances $\lambda_{dt\mu-p,d,t}(E_{t\mu})$ for the $t\mu$-atom spin $F = 0$ are shown in Fig. 2. This picture is taken from [13] where the first systematic calculation of $\lambda_{dt\mu}$ was made. Improved calculations [14] for $\lambda_{dt\mu-d}$, $F = 0, 1$, including the quadrupole corrections (Q) in matrix elements, are shown in Fig. 3. The following remarkable features are evident from these figures:

1. Resonance formation of the $dt\mu$-molecule on HD molecules is the most intensive.

2. The resonance positions correspond to relatively high $t\mu$-atom energies, that is, to high temperatures ($T \sim 10^3 K$) for the thermalyzed muonic atoms.

3. The positions of the resonances of each type corresponding to various vibration level of the complex $\nu = 3, 4, 5$. The nearest resonance for $\lambda_{dt\mu-d}^0$ is placed at $E_{t\mu} \simeq 0.5 \, eV$. It means that the nearest "sub-threshold" resonance (corresponding to $\nu = 2$) lies close to zero at the negative $t\mu$-atom energy $E_{t\mu} \simeq -(10 - 12) \, meV$. Negative energy means that for the most intensive dipole transitions $|K_f - K_i| = 1$ the energy excess arises which cannot be transferred in two-particle reaction (2).

For the highest multiple transitions

$$\nu = 2; \quad K_i = 0, 1 \rightarrow K_f = 2, 3, 4$$

process (2) becomes possible but its intensity is two orders of magnitude lower than that of the main transitions. However, as follows from the modern theory, the influence of this sub-threshold resonance turns out to be much stronger, as we will discuss later.

With the temperature increase, the resonance pictures are modified due to the change of the population of the DX-molecule rotational states and the molecule thermal motion. The formation rates of $\lambda_{dt\mu-d}$ and $\lambda_{dt\mu-t}$ as functions of $E_{t\mu}$ for $T = 300 \, K$ are presented in Fig. 4. The Maxwell distribution for the thermalyzed $t\mu$-atoms is shown in one of them ($\lambda_{dt\mu-t}$). As is seen, this distribution only slightly overlaps the nearest resonance.

The resonances for $\lambda_{dt\mu}$ at $T = 1000 \, K$ are presented in Fig. 5. In this case the Maxwell distribution considerably overlaps the most intensive resonances for $dt\mu$ formation on D_2, DT and HD molecules. Unfortunately, this high temperature is not yet achieved in experiment. The temperature $T = 800 \, K$ is the highest at which the measurements were made (in Dubna).
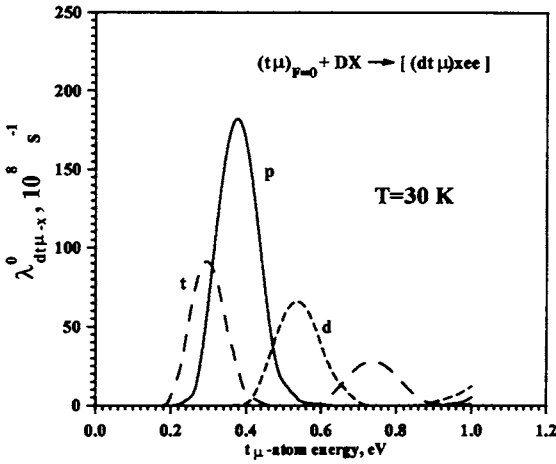
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Figure 2: The dtμ-molecule formation rates for the tμ-atom spin F = 0 and temperature T = 30 K [13].
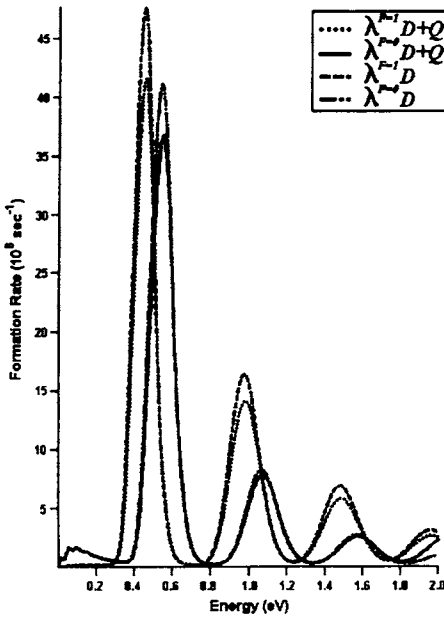

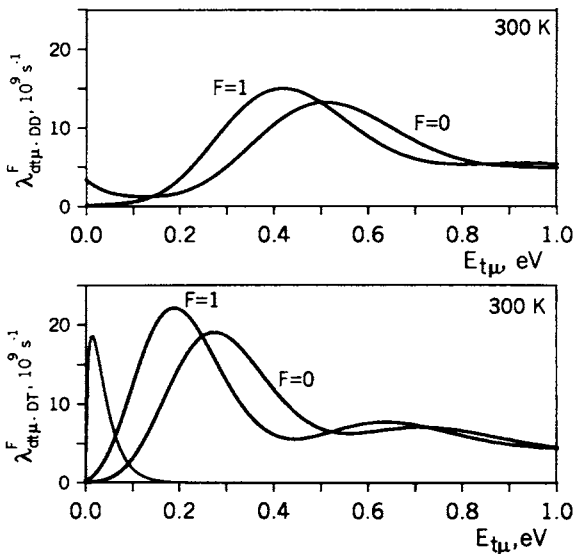*Figure 3: Improved calculations [14] of $\lambda_{dt\mu-d}$ for T = 30 K in comparison with those in Fig.2 [13].*

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Figure 4: The dependence of $\lambda_{dt\mu-d}$ (top) and $\lambda_{dt\mu-t}$ (below) on the $t\mu$-atom energy for $T = 300\,K$ (calculations [14]). Maxwell distribution is shown in the bottom picture.
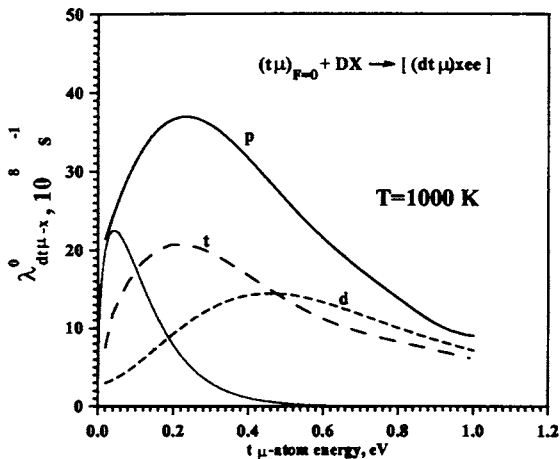

Figure 5: The $dt\mu$-molecule formation rates on D_2, DT and HD molecules as a function of $E_{t\mu}$ for $T = 1000\,K$ (calculations [14]) and Maxwell distribution.

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3   Epithermal spike and steady state

In which way do $t\mu$-atoms acquire the resonance values of their energy? As we mentioned, a substantial part of $t\mu$ have an initial (after cascade) energy $E_{t\mu} > 1\,eV$. In elastic collisions $t\mu + t$, $t\mu + d$ these atoms are quickly thermalyzed. The thermalization time is $\sim ns$ for the LHD of a mixture. Accordingly, the time distribution of the fusion reaction products (neutrons) should have two component: the quick "spike" corresponding to the first pass through the resonances and the much slower "steady state" component. An example of such a distribution is presented in Fig. 6. It is the time spectrum of the $d - t$ neutrons measured by us at $C_t = 0.7$, $\varphi = 0.4\,LHD$ and $T = 160\,K$.

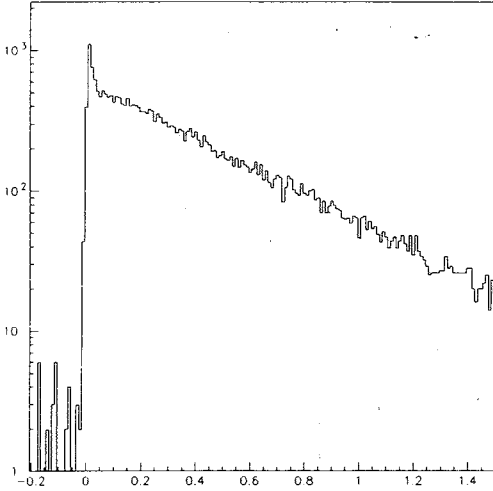*Figure 6: Experimental neutron time distribution measured by the Dubna group in the D/T mixture under the following conditions: $\varphi = 0.4\,LHD$, $C_t = 0.7$, $T = 160\,K$.*

Due to shortness of the epithermal spike and ambiguity in the $t\mu$-atom initial energy it is hard to interpret this effect. That is why the main efforts of different experimental groups were concentrated on the steady state study for which the $t\mu$-atom energy spectrum is a Maxwell distribution.

For convenience the comparison of the measurements with the theoretical calculations are performed for the so-call "effective" $dt\mu$-molecule formation rate as a function of temperature. This is obtained by integrating over all possible initial states, averaging over all final states and convoluting with the Maxwell spectrum $W(E_{t\mu}, T)$. Such calculations made in [14] for the D/T mixture are presented in Fig. 7.

For the steady state the time distribution of fusion neutrons has the form

$$dN_n/dt = \epsilon_n \cdot \lambda_c \cdot \varphi \cdot exp[-(\lambda_0 + \omega \cdot \lambda_c \cdot \varphi) \cdot t], \qquad (3)$$

where ϵ_n is the neutron detection efficiency, ω is the muon losses in the cycle which

are mainly the probability of muon sticking to helium in fusion reactions: mainly in $d + t$ (ω_s) and also, with lower weight, in the accompanying reactions $d + d$ and $t + t$. The cycling rate λ_c means the inverse of the averaged time between the closest cycles. It involved the $d\mu$ - $t\mu$ transfer time and the $dt\mu$-molecule formation time. It follows from Eq. 3 that the neutron yield Y_n per muon is

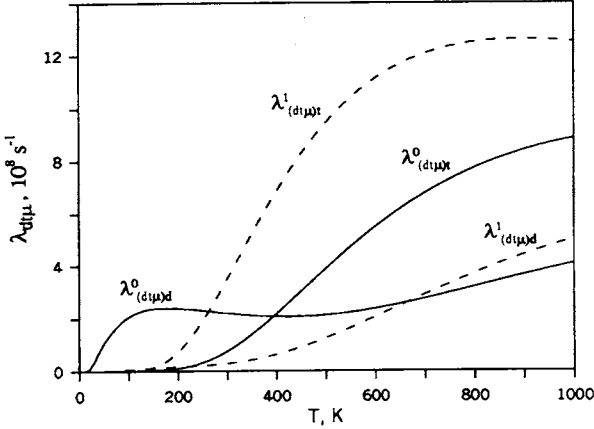$$Y_n^{-1} = \omega + \frac{\lambda_0}{\lambda_c \cdot \varphi}.$$

Figure 7: Temperature dependencies of the $dt\mu$-molecule formation on D_2 and DT molecules for $F_{t\mu} = 1, 0$, as calculated in [14]

The expression for λ_c has the form

$$\frac{1}{\lambda_c} = \frac{q_{1s} \cdot C_d}{\lambda_{dt} \cdot C_t} + \frac{1}{(\lambda_{dt\mu-d} \cdot C_{DD} + \lambda_{dt\mu-t} \cdot C_{DT})}. \qquad (4)$$

To extract the values $\lambda_{dt\mu-d}$ and $\lambda_{dt\mu-t}$ one should analyze, using formula (4), the experimental values of λ_c measured at different tritium concentrations changing the relative population of D_2 and DT molecules.

The set of the experimental conditions (density and temperature) for measurements of different groups is indicated in Fig. 8. As seen from this figure, most data are concentrated at low temperatures (less than $T \sim 300\,K$). Practically all groups carried out the measurements with the liquid D/T mixture (LAMPF [9], Dubna [15], PSI [16], RIKEN-RAL [17]). All these groups, except Dubna, also made measurements with solid D/T. As to the gaseous mixture, the PSI measurements were limited in density and temperature ($\varphi \leq 0.24\,LHD$, $T = 40\,K$ and $\varphi = 0.01\,LHD$, $T = 300\,K$). Only LAMPF and Dubna could realize high-density ($\varphi \leq 1\,LHD$), high-temperature ($T \leq 800\,K$) targets. It turns out that the most surprising results relate to low temperature region, where the "standard" theory predicted a low MCF intensity.
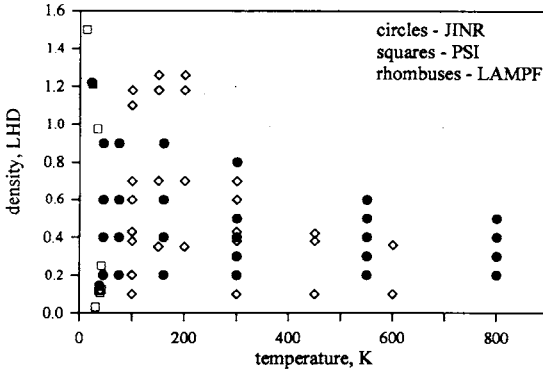
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Figure 8: The experimental conditions (density and temperature) for the MCF process study in the D/T mixture.

4 Low-temperature steady state

The experimental results for $\lambda_c(C_t)$ obtained by different groups at $T \leq 40\,K$ are presented in Fig. 9.
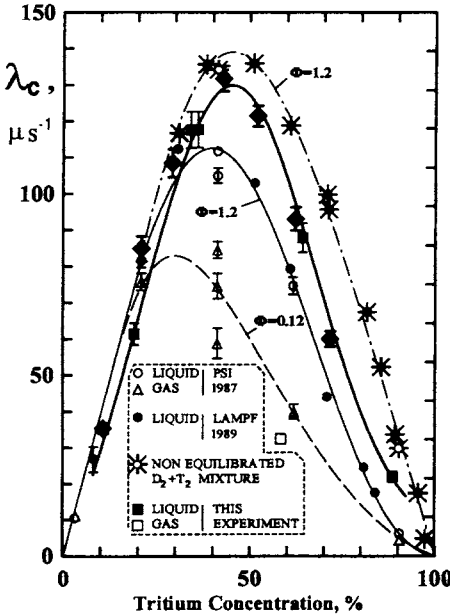

Figure 9: The dependencies $\lambda_c(C_t)$ measured at low temperatures $\leq 40\,K$ and different densities up to $\varphi = 1.45\,LHD$. The data are normalized to LHD.

As follows from the data presented in Fig. 9, the MCF process at low densities is very intensive in contradiction with the "standard" theory. It was proved that the effect was fully provided by $\lambda_{dt\mu-d}$, that is, the $dt\mu$ formation on D_2 molecules, and significantly depended on density. The highest neutron yield $Y_n = 124 \pm 10$ [16] was

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measured in the solid non-equilibrium D/T mixture with the highest D_2 molecule concentration for given C_t.

The LAMPF and Dubna groups extended the measurements to the high density ($\varphi \leq 1\,LHD$) gaseous D/T mixture. Analysis of the experimental data on $\lambda_c(C_t)$ with expression (4) allows the determination of $\lambda_{dt\mu}$ and q_{1S} as a function of density. The corresponding dependencies are presented in Fig. 10-11. They include the PSI measurements ($\varphi \leq 0.24\,LHD$, $T \leq 40\,K$) and the results obtained by the LAMPF and Dubna groups at higher densities and temperatures ($\varphi \leq 1\,LHD$, $T \leq 300\,K$).
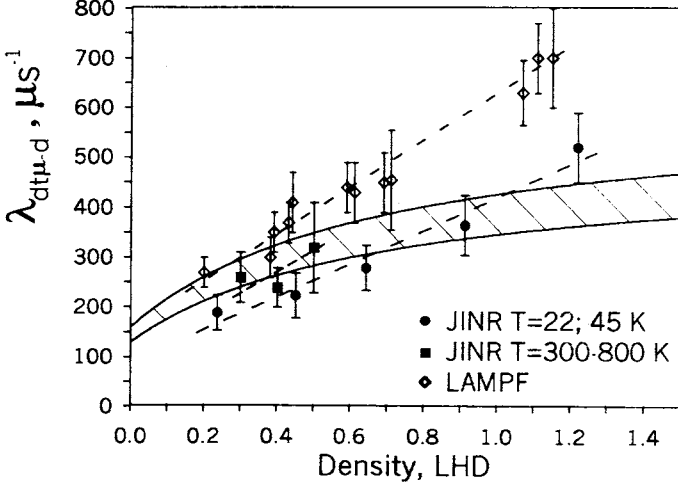

Figure 10: Density dependence of $\lambda_{dt\mu-d}$. The shading is the parametrization made in [16]. Dark points are the Dubna measurements [21], open points are the results of [9]

As seen from Fig. 10, the $dt\mu$ formation rate on molecules D_2 strongly depends on density and achieves its maximum value $\lambda_{dt\mu-d} \simeq 500\,\mu s^{-1}$ at $\varphi = (1.2 - 1.4)\,LHD$. To explain the high MCF intensity at low temperatures and its non-trivial density dependence, the mechanism of triple collisions was suggested in [18]. According to this work, the resonance $dt\mu$ formation occurs at the sub-threshold resonance $\nu = 2$ through to the triple collisions process

$$t\mu + D_2 + M \longrightarrow [(dt\mu), d, 2e] + M' \qquad M = D_2, DT, T_2 \ . \tag{5}$$
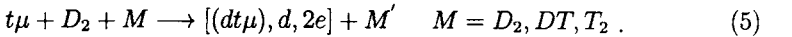
The "additional" second molecule M plays a role of a spectator which carries away the energy excess. As (5) is a three particle process, it must depend on the density of molecules M.

Qualitatively, the scheme (5) explains both the high values of $\lambda_{dt\mu-d}$ and its density dependence. However, in spite of many efforts undertaken to calculate its intensity (see, for example, [19, 20]), the quantitative explanation is not obtained yet.

The problem is to explain the temperature dependence $\lambda_{dt\mu}(T)$. It seems that the resonance character of process (5) (though on the sub-threshold resonance) implies a decrease of $\lambda_{dt\mu-d}$ with temperature to the nearest "positive" resonance. However, as follows from Fig. 12, this value remains practically constant up to $T = 500\,K$.
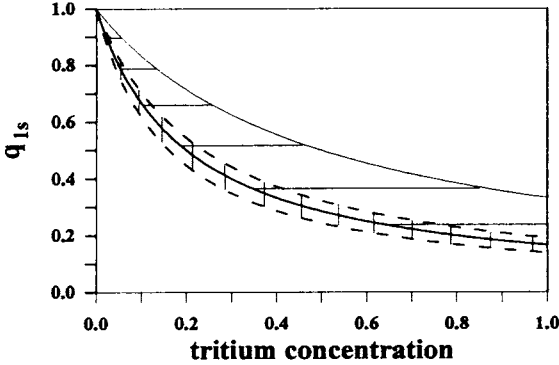

Figure 11: The dependencies $q_{1S}(C_t)$. The horizontal shading is the PSI parametrization [16] based on the measurements at low temperatures $\leq 40\,K$. The vertical shading is the Dubna points [21] measured at $\varphi = (0.2 - 1.2)\,LHD$ and $T = 20 - 800\,K$.
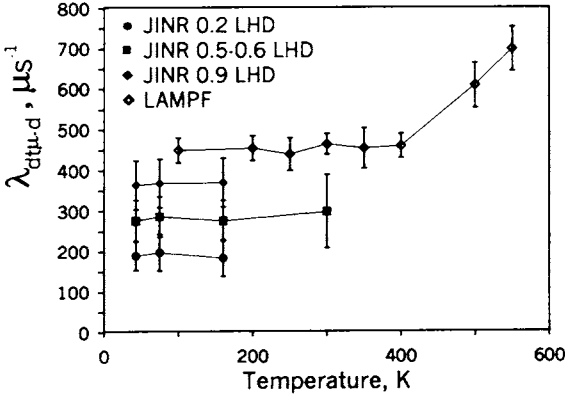

Figure 12: The temperature dependence of $\lambda_{dt\mu-d}$. Open points are the results of [9]. Dark points are the Dubna data.

Another possible reason for the dependence $\lambda_{dt\mu-d}(\varphi)$ could be, as theory predicts [4], the density influence in q_{1S}. Surprisingly, q_{1S} turns out to be independent of density. This is demonstrated in Fig. 11, where the data of PSI [16] and Dubna [21] are presented in the wide interval $\varphi = (0.01 - 1.2)\,LHD$.

5   High-temperature steady state

Measurement of the $dt\mu$-molecule formation rate at high temperatures $T > 300\,K$ is valid due to the fact that the Maxwell distribution of the $t\mu$-atom energy overlaps resonances $\lambda_{dt\mu}(E_{t\mu})$ more fully the higher the temperature. Such experiments were carried out by the LAMPF group [9] at $T \leq 540\,K$, and by the Dubna group [21]

at $T \leq 800\,K$. Really, the nearest resonance $\lambda_{dt\mu-t}(E_{t\mu})$ begins to be influenced at these temperatures. The measured dependencies $\lambda_c(C_t)$ are shown in Fig. 13.
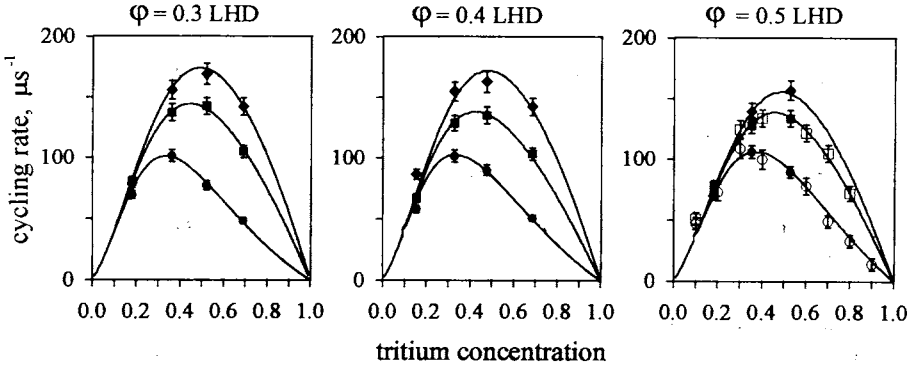

Figure 13: The dependencies $\lambda_c(C_t)$ measured at different densities and temperatures. Dark points are the Dubna results [21]: circles - $T = 300\,K$, squares - $T = 550\,K$ and rhombuses - $T = 800\,K$. Open points are the LAMPF data [9]: circles - $T = 300\,K$, squares - $T = 550\,K$. Lines are the fit of the Dubna points to (4).

One can see from this figure that λ_c increase with T and that its maximum position moves to higher C_t where the concentration of DT-molecules is higher. This directly proves the influence of the opening resonance for $\lambda_{dt\mu-t}$.

Analysis of $\lambda_c(C_t)$ allows the determination of the $dt\mu$-molecule formation rate on DT-molecules as a function of temperature and its comparison with the calculated one presented in Fig. 7. The results are presented in Fig. 14.
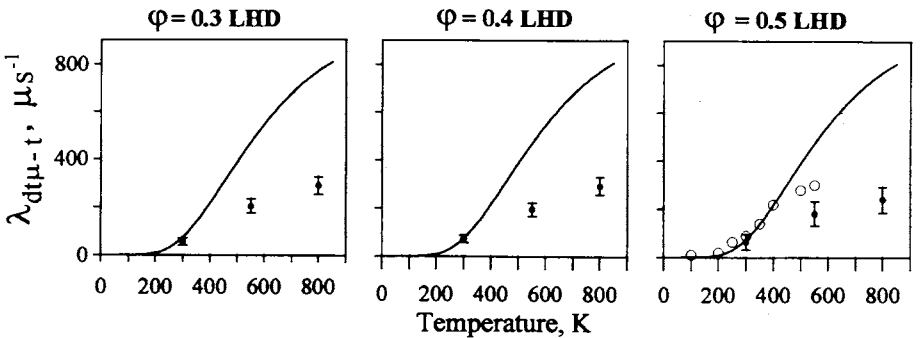

Figure 14: Temperature dependence of $\lambda_{dt\mu-t}$. Dark points are the Dubna results [21], open circles are the LAMPF measurements, lines are the calculations [14].

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As follows from Fig. 13, 14, two sets of the experimental values of $\lambda_c(C_t)$ and $\lambda_{dt\mu-t}(T)$ are in rough agreement. However, there is the significant difference between them and the theory.

6 Epithermal effects in low-density D/T mixture

As serious indications of disagreement between the measured and theoretical data on the resonances $\lambda_{dt\mu}(E_{t\mu})$ intensity have been obtained, it would be very desirable to try to feel these resonances in an independent way. One of them is the analysis of a spike in the fusion neutron time spectrum (see Sect. 3) caused by passage of "hot" $t\mu$-atoms through the resonances. Due to a fast deceleration rate ($\lambda_d \cdot \varphi \sim 10^9 \, s^{-1}$) one should made such measurements at low density where the spike can be confidently observed and analyzed.

The corresponding experiments with the D/T mixture at $\varphi = 0.01 \, LHD$ and various tritium concentrations were carried out in PSI [22]. The examples of the neutron time distributions observed in [22] are presented in Fig. 15.
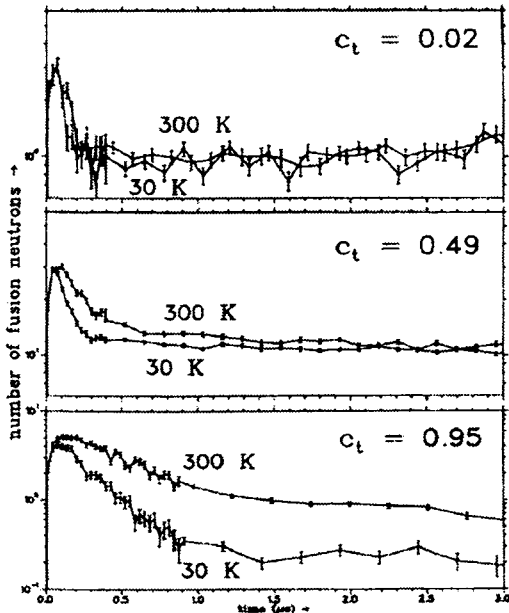

Figure 15: Neutron time distributions measured in [22] with the D/T mixture at $\varphi = 0.01 \, LHD$ and wide range of tritium concentrations. Lines are the Monte-Carlo calculations.

Spikes caused by the passage through the resonance are clearly seen at small times. Their width depends on the tritium concentration: the shortest spike takes place at a low tritium concentration where thermalization is mainly due to $t\mu + d$ scattering, whose cross section is much larger than for $t\mu + t$ scattering [23]. For the highest tritium concentration the steady state is not even achieved.

Analysis of the data [22] is rather complicated because it involves the initial energy distribution of $t\mu$-atoms, their elastic and inelastic (spin exchange) cross sections, the position and intensity of resonances. Due to many processes involved, it should be made with using the Monte-Carlo simulation. It followed from the analysis that more or less satisfactory agreement of measurements and calculations could be obtained only under the assumption that the essential part ($\simeq 0.5$) of $t\mu$-atoms is initially thermalized, as follows from the consideration of [24]. In other cases the resonance intensity turned out to be significantly smaller than the theory [14] predicted.

The problem of the initial $t\mu$-atom energy is absent for a triple H/D/T mixture with very low tritium contamination (~ 0.01). In this case practically all $t\mu$-atoms are formed due to the transfer processes $p\mu+t \rightarrow t\mu+p$ and $d\mu+t \rightarrow t\mu+d$, in which the $t\mu$-atom acquires the energies $46\,eV$ and $19\,eV$ respectively. Such a mixture ($C_t = 0.01$, $\varphi = 0.05\,LHD$) was used in PSI [25] for the direct measurements of ω_s. Simultaneously, the authors measured and analyzed neutron time spectra. Due to extremely low $t\mu + p$ and $d\mu + p$ cross sections, the thermalization spikes are observed even at relative high density.

The data obtained in this work were also analyzed in [22]. It turned out that in this case simpler for analysis the results indicate significant disagreement of the Monte-Carlo simulations with the measured spectra if one takes the theoretical values of the resonances intensities. Again, the theoretical values seem to be substantially overestimated.

7 TOFF $t\mu + D_2$

The independent way to feel resonances was suggested and realized in TRIUMF [26]. The advantage of the method is that the energy of the $t\mu$-atom passing through the resonance is directly measured. The scheme of the experiment is shown in Fig. 16.
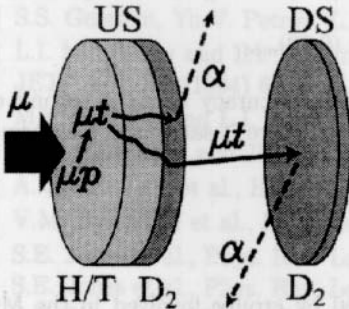

Figure 16: Scheme of experiment [26].

$t\mu$-atoms are formed in the first solid layer US (H_2+T_2), decelerated in the next layer (solid D_2) and pass through vacuum space to reach the interactive layer DS (D_2). The $t\mu$-atom energy is measured as the time of flight between the US and

DS layers. The fusion α-particle yield was measured as a function of this time. The results are presented in Fig. 17.
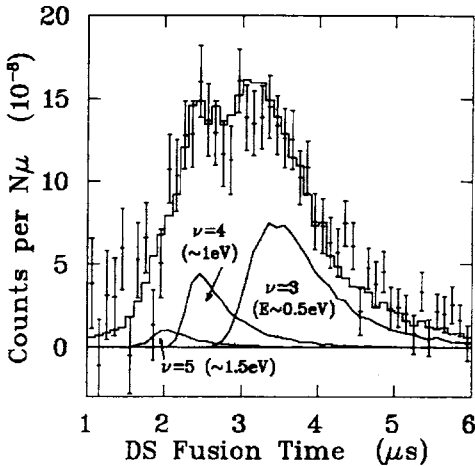

Figure 17:
The dependence of the $d + t$ α-particle yield on the $t\mu$-atom energy measured in [26]. The line is the Monte-Carlo simulation.

Of course, the energy resolution is bad, which is due to the large angular acceptance for $t\mu$ leaving the layer US (D_2) and to some deceleration in the interactive layer before fusion. Nevertheless, different resonances corresponding to vibrational excitement $\nu = 3, 4, 5$ can be distinguished. The disadvantage of the method is its extremely low efficiency. Losses of $t\mu$-atoms occur at all stages: in the emission from the US $(H/T$ and $D_2)$ layers and especially in flight between US and DS. As a result, only (2036 ± 116) α 's were detected per $6.02 \cdot 10^8$ incoming muons.

The Monte-Carlo analysis involved all stages in the $t\mu$-atom history and the α-particle registration. The corresponding cross-sections for the $t\mu + p, d, t$ processes [23] were used. The resonance intensities were varied with the scaling factor S ($S = 1$ corresponds to theory). The best fit line shown in Fig. 17 corresponds to

$$S = 0.73 \pm (0.16)_{meas} \pm (0.09)_{mod},$$

where the first error arises from the measurement accuracy and the second one from the uncertainty of the model. As can be seen, there is satisfactory agreement between the data [26] and the calculations [14].

8   Conclusions

Consideration of the experimental data obtained by groups involved in the MCF study and the use of different methods makes it possible to draw the following conclusions:

1.   The most extensive measurements were carried out for the low-temperature

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steady state $(T \leq 300\,K)$. The fundamental MCF value - the $dt\mu$-molecule formation rate on D_2-molecule - has been measured as a function of density and temperature. The results of different authors [9, 10, 16, 15, 17] are in good agreement with one other. For the theoretical explanation it is necessary to modify the "standard" Vesman scheme by including in it the tree-body reaction (5) on the "sub-threshold" resonance. This allows only a qualitative understanding of the process, the quantitative agreement with experiment is not achieved yet.

2. The first experimental efforts to investigate the region of the real resonances were made by studying the high-temperature steady state $(T \leq 800\,K)$ [9, 21]. The result obtained indicate significant difference between the measurements and theory for the $dt\mu$-molecule formation rate on D/T molecules. The same is obtained from the study of the epithermal effects [22] but here the interpretation is complicated by the uncertainty in the initial energy distribution of $t\mu$-atoms.

A peculiar way to "feel" resonances was developed in TRIUMF [26]. The advantage of the method is the direct measurement of the energy of the $t\mu$-atom participating in the MCF cycle. The results [26] on the resonance intensity are in satisfactory agreement with the "standard" theory. However, the extremely low efficiency of the method and the necessity to simulate the μ-atom history can cause problems with the absolute normalization.

3. The study of the steady state seems to be more reliable due to its simplicity. It would be very important to carry out measurements with D/T and H/D/T mixtures at the highest temperatures $T = 1000 - 2000\,K$ for which the Maxwell distribution of the μ-atom energy overlaps the most intensive resonances. The appropriate target is now developed in Sarov [27].

References

[1] L.I. Ponomarev, Contemp. Phys. 31 (1990) 219.

[2] W.H. Beunlich, P. Kammel, J.S. Cohen, M. Leon, Ann. Rev. Nucl. Sci. 24 (1998) 151.

[3] S.S. Gerstein, Yu.V. Petrov, L.I. Ponomarev, Uspechi Fiz. Nauk 160 (1990) 3.

[4] L.I. Menshikov and L.I. Ponomarev, Pis'ma Zh. Exp. Teor. Fiz. 42 (1985) 542; JETP Lett. 39 (1984) 663.

[5] M.P. Faifman and L.I. Menshikov, Hyperfine Inter. 138 (2001) 61.

[6] V.E. Markushin and T.S. Jensen, Hyperfine Inter. 138 (2001) 71.

[7] A.V. Kravtsov et al., Hyperfine Inter. 138 (2001) 103.

[8] V.M. Bystritski et al., Phys. Lett. B 94 (1980) 476.

[9] S.E. Jones et al., Phys. Rev. Lett. 51 (1983) 1757;
S.E. Jones et al., Phys. Rev. Lett. 56 (1986) 588;
S.E. Jones et al., Muon Cat. Fusion 1 (1987) 21;
A.J. Caffrey et al., Muon Cat. Fusion 1 (1987) 53.

[10] W.H. Breunlich et al., Phys. Rev. Lett. 58 (1987) 329.

[11] D.V. Balin et al., Zh. Eksp. Teor. Fiz. 92 (1987) 1543 (Sov. Phys. JETP 65 (1987) 866)

[12] E. Vesman, Pis'ma Zh. Eksp. Teor. Fiz. 5 (1967) 113 (Sov. Phys. JETP Lett. 5 (1967) 91)

[13] M.P. Faifman, L.I. Menshikov and T.A. Strizh, Muon Cat. Fusion 4 (1989) 1.

[14] M.P. Faifman et al., Hyperfine Inter. 101/102 (1996) 179.

[15] Yu.P. Averin et al., Hyperfine Inter. 118 (1998) 121.

[16] P. Ackerbauer et al., Nucl. Phys. A 652 (1999) 311.

[17] K. Ishida et al., Huperfine Inter. 118 (1998) 203.

[18] L.I. Menshikov and L.I. Ponomarev, Phys. Lett. B 167 (1986) 141.

[19] M. Leon, Muon Cat. Fusion 1 (1987) 163; Phys. Rev. A 49 (1994) 4438.

[20] Yu.V. Petrov, V.Yu. Petrov, H.H. Schmidt, Phys. Lett. B 331 (1994) 266.

[21] V.R. Bom et al., Hyperfine Inter. 138 (2001) 313.

[22] M. Jeitler et al., Phys. Rev. A 51 (1995) 2881.

[23] L. Bracci et al., Muon Cat. Fusion 4 (1989)247;
J. Cohen, Phys. Rev. A 43 (1991) 3460; 43 (1991) 4668;
A. Adamczak et al., Preprint JINR E4-95-488, Dubna, 1995.

[24] V.E. Markushin, Phys. Rev. A 50 (1994) 1137.

[25] C. Petitjean et al., Hyperfine Inter. 82 (1993) 273;
K. Low et al., Hyperfine Inter. 82 (1993) 313.

[26] M.C. Fujiwara et al., Phys. Rev. Lett. 85 (2000) 1642.

[27] A.A. Yukhimchuk et.al., private communication, Sarov, 2003.

Фильченков В. В., Графов Н. Н.   E15-2003-96
Статус исследования реакции мюонного катализа $d+t$

Рассмотрен статус исследования реакции мюонного катализа $d+t$ в D/T-смеси. Проведено сравнение экспериментальных данных, полученных различными методами, с теоретическими предсказаниями. Обозначены нерешенные проблемы в интерпретации результатов измерений. Отмечена важность проведения измерений при высоких температурах.

Filchenkov V. V., Grafov N. N.   E15-2003-96
Status of the Investigation of the Muon Catalyzed $d+t$ Reaction

The status of the study of the muon catalyzed fusion (MCF) reaction $d+t$ in the D/T mixture is briefly considered. The experimental data obtained by the different methods are compared with the theoretical predictions. Unsolved problems in the explanation of the measured results are indicated. The importance of the high temperature measurements is stressed.