MUON CATALIZED *dd*- and *dt*-FUSION

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Introduction

The possibility of formation of the mesomolecules like $dd\mu$ and $pd\mu$ followed by fusion of the nuclei in the mesomolecules was first pointed out by A.D.Sakharov (1946) and F.Frank (1947). The muon released after the fusion reaction is able to form a new mesomolecule thus serving as a catalyzer of the nuclear fusion. Later on Ja.B.Zeldovich developed the theory of this process in the natural for that time version of non-resonant mesomolecular formation. L.Alvarez (1956) was first to observe experimentally the mesocatalysis of a nuclear fusion reaction in the channel

$$d\mu + p \rightarrow dp\mu \rightarrow {}^3\mathrm{He} + \mu + 5.4\ \mathrm{MeV}.$$

This discovery created a lot of excitation throughout the world. It was considered a potential new source of energy production. But soon the formation rates of the $pd\mu$ and $dd\mu$ molecules were found to be too low for any practical application of this process. Also, the formation rate of the $dt\mu$ molecule, most perspective for the energy production, was expected to be similarly low. Moreover, D.Jackson (1957) and S.Gerstein (1960) pointed on a principal limitation for the number of cycles catalyzed by one muon. This limit is set by the probability of muon sticking to the ^{4}He nuclei created in the dt-fusion process. The authors estimated this probability to be about one percent that corresponded to the maximum number of fusions on a level of 100. But even this limit was considered to be far from being reachable because the observed mesomolecular formation rates were so low that only one fusion cycle was possible during the muon lifetime. As a result, the interest for the muon catalized fusion (μCF) slowly died away.

Meanwhile, an interesting observation was reported in 1964 by the V.P.Jelepov's group at JINR (Dubna). The rate $\lambda_{dd\mu}$ measured at $T = 300$ K turned to be an order of magnitude higher than the already known rate $\lambda_{dd\mu}$ in liquid deuterium. This observation was in contradiction with the expected independence of $\lambda_{dd\mu}$ on temperature. A possible explanation was given by E.A.Vesman (1967) who assumed the existence of a weakly bound state in the $dd\mu$ molecule. In this case the formation rate of the $dd\mu$ molecule might be increased due to the resonant transfer of the released energy to the mesomolecular complex $[(dd\mu, d)2e]$. The theory of resonant mesomolecule formation was later developed by the L.I.Ponomarev's group. The precise calculations not only proved the existence of the weakly bound level in the $dd\mu$ molecule ($\varepsilon_{11} = -1.9$ eV) but also predicted an analogous level in the $dt\mu$ molecule ($\varepsilon_{11} = -0.6$ eV), that should lead to an extremely high formation rate of the $dt\mu$ molecule. This prediction was confirmed in 1979 in the experiment performed by the V.P.Jelepov's group in Dubna which demonstrated that $\lambda_{dt\mu} \approx 10^8\ \mathrm{s}^{-1}$.

After that observation the interest to the mesocatalysis sharply increased. Several experiments started in USA (LAMPF), Switzerland (PSI), Russia (PNPI), Canada (TRIUMF), Japan (KEK). At the same time theorists continued working on more precise μCF theory. Some studies were started on possible utilization of the μCF as an intensive source of 14 MeV neutrons and even as an energy source. As a result of these efforts, a very high level of understanding of the μCF process is reached today. An important contribution to this progress was made by the experiments performed by the PNPI group at the PNPI synchrocyclotron and later at the Swiss meson factory (PSI). The success of these experiments was due to a new experimental method which has made it possible to register the charged products of the fusion reactions. This article presents a brief account of the results obtained by the PNPI group.

Experimental method

Prior to our experiments, the usual method of investigation of the muon catalyzed fusion was registration of neutrons produced in the fusion reactions. This method proved to be quite effective but still it has some limitations: the channels where no neutrons are produced in the final state are not detected, the channels with muon sticking to helium are not identified, there are difficulties in measuring the absolute reaction rates.

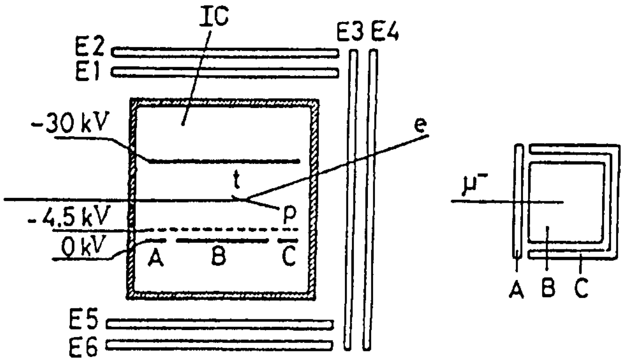

Fig. 1. Scheme of the first ionization chamber for the $d\mu d$-fusion studies (PNPI, 1980). Cathode to anode distance – 10 mm, grid to anode distance – 1 mm, dimensions of the anode B – 35×35 mm^2, gas pressure (D_2) – 90 atm.

The basis of our method [1] is the use of a high pressure hydrogen (deuterium) filled ionization chamber as a "sensitive target" (Fig. 1). The chamber registers the incoming muons as well as the charged products of the nuclear fusion catalyzed by these muons. The analysis of muon signals enables us to select the muons stopped in the central part of the chamber sensitive volume and thus to exclude the wall effect on the registration efficiency of the fusion products. As a result, the 100% efficiency in registration of the charged fusion products is reached.

A peculiar feature of the method is the high (up to 200 atm) pressure of hydrogen used in the chamber . It was not obvious in the beginning whether there will be any visible signals at such a pressure at all in view of possible electron-ion recombination in a track. Fortunately, the recombination effect turned out to increase quite slowly with the increase of the pressure. Besides, the recombination appeared to be nearly independent on the track orientation relative to the direction of the electric field. Therefore, the recombination effect is just some shift of the observed peaks towards the smaller energies, practically without degradation of the energy resolution. So, the energy spectra could be successfully measured in the presence of the recombination effect. Moreover, in some cases this effect proved to be even useful. In particular, it gave us an opportunity for direct measurement of the muon sticking to helium by moving apart the peaks belonging to $(\mathrm{He})^{++}$ and $(\mathrm{He}\mu)^{+}$. Without recombination these peaks would coincide with each other. As an example, Fig. 2 shows an amplitude spectrum of the dd-fusion products measured in one of our first experiments [2].

The high registration efficiency allows to detect two and more fusions catalyzed by one muon. It is the base of the method (we call it "the survived muon method") in which we select only those events when we are sure that the muon was released after the first fusion and that it did not decay and was not captured till at least the next fusion. This method turned out

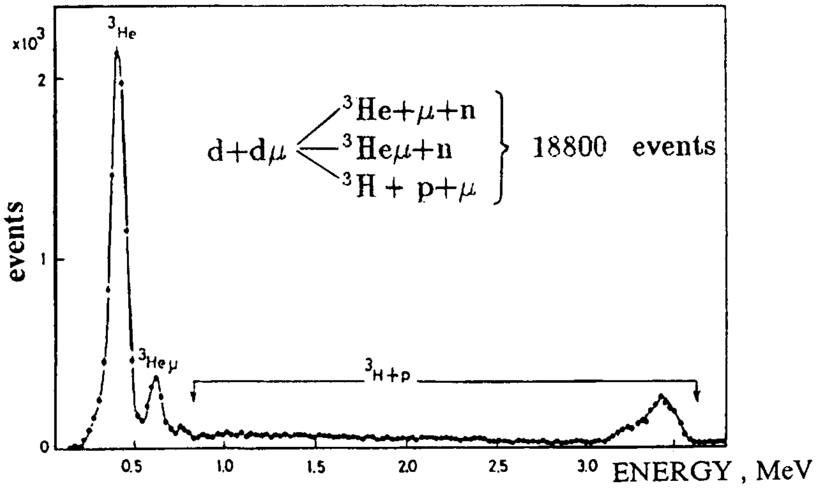

Fig. 2. Amplitude distribution of the *dd*-fusion events, measured with the IC. The chamber parameters are given in Fig.1. One can see the separation of the $(\mathrm{He})^{++}$ and $(^3\mathrm{He}\mu)^+$ peaks. The ^{3}H peak should have the amplitude of 0.9 MeV. The amplitudes of $^3\mathrm{He}+p$ signals are distributed from 0.9 MeV to 3.6 MeV because the protons escape sometimes from the chamber sensitive volume. The noise level is $\sigma = 30$ keV, the registration threshold is 130 keV, the registration efficiency is 99%, the background events contribution is 0.1%.

to be the most accurate in determining the absolute $dd\mu$ molecule formation rate (accuracy of 3%), as well as in measuring the muon sticking probability.

Further experiments used several modifications of the ionization chamber differing mostly in the geometry and in the number of the anodes. The precise measurements of the $d\mu d$-fusion temperature dependence were of special interest. For this purpose, a modification of the IC with helium cooling was designed [3]. It allowed the IC to operate in the temperature range of 30–300 K with the possibility to stabilize the temperature and to measure it at any point with the accuracy of ±0.3 K. In the experiments carried out at PSI, the IC was surrounded with the neutron counters hodoscope extending potentialities of the method. In particular, this improved the registration conditions for the fusion events appearing shortly after the muon stop in the time interval of 0–200 ns.

The IC method proved to be beyond any competition in the case of the $d\mu d$-fusion studies. However, some complications occurred in its application for investigation of the $d\mu t$-fusion caused by the electrons from the tritium β-decay in the IC sensitive volume. To reduce the tritium background, the chamber anode was divided into 19 separate anodes, 3 mm in diameter each. At 100 atm pressure, the range of the α-particles from the dt-fusion is 1 mm. Therefore, all the ionization produced by the α-particle is collected mostly by one of the anodes while the background current is distributed between the 19 anodes. This design allowed us to study the $d\mu t$-fusion in D/T mixtures with the tritium concentration up to 3%.

Study of $d\mu d$-fusion

Investigation of the $d\mu d$-fusion in D_2 molecules gives a unique opportunity for quantitative comparison with the μCF theory. It is just in this case the resonance mechanism of the mesomolecular formation is displayed in the most pronounced way. Moreover, this mechanism is not shadowed by the by-side processes like incomplete thermalization of the $d\mu$ atoms. The $d\mu d$-fusion leads to three different reaction channels:

$$d\mu + d \rightarrow dd\mu \rightarrow {}^3\text{He}{+}n + \mu; \qquad \rightarrow {}^3\text{He}\mu + n; \qquad \rightarrow {}^3\text{H}{+}p + \mu. \qquad (1a, 1b, 1c)$$

This set of reactions is determined by three main parameters: the formation rate of the ddμ molecule, $\lambda_{dd\mu}$; the probability of muon sticking to helium, $\omega_{dd} = Y(1b)/[Y(1a) + Y(1b)]$; the relative yield of the isotopically symmetric channels, $R = [Y(1a) + Y(1b)]/Y(1c)$. Already in our initial experiments (Gatchina, 1980–1983) we succeeded in measuring all the three parameters [4]:

$$\lambda_{dd\mu} = (2.76{\pm}0.08)\cdot\ 10^6\ \text{s}^{-1};\ R = Y({}^3\text{He}{+}n)/Y({}^3\text{H}{+}p) = 1.39 \pm 0.04; \omega_{dd} = 1.122 \pm 0.003.$$

Here $\lambda_{dd\mu}$ is normalized to the liquid hydrogen density. The measurements were carried out at deuterium pressure $P = 90$ atm and temperature $T = 300$ K. Note that in the previous experiments only one parameter, $\lambda_{dd\mu}$, was measured. After that we have measured the temperature dependence of the $d\mu d$-fusion rate in the range of $T = 50$–300 K (PNPI, 1987). Finally, these studies were continued in a joint experiment at PSI where we performed the most detailed and precise investigations of the $d\mu d$-fusion process in the temperature range of $T = 28$–350 K. The data from this experiment are only partly analyzed at present.

$dd\mu$ molecule formation rate

Fig. 3 illustrates the situation in the $\lambda_{dd\mu}$ measurements at the time of publication of our first result in 1983. The very large (4 times) difference between our $\lambda_{dd\mu}$ value and that from the Dubna results was a shock.

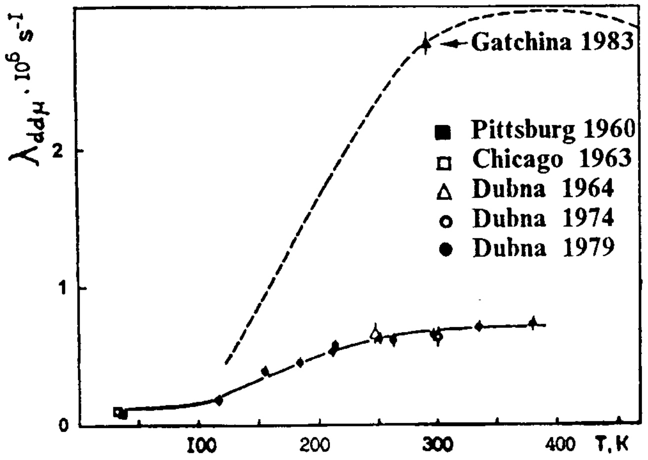

Fig. 3. The situation in the measurements of the ddμ molecule formation rate in deuterium for 1983. All the experimental points are normalized to the liquid hydrogen density. The "Dubna 1979" results are relative, normalized to the "Dubna 1964" and "Dubna 1974" data. The dotted line is the result of renormalization of the "Dubna 1979" data to our experimental point.

This difference forced us to repeat the measurements at various conditions. We showed, in particular, that the $\lambda_{dd\mu}$ value normalized to the liquid hydrogen density does not depend on pressure in the interval from 51 atm to 93 atm. Thus, the observed difference could not be explained by somewhat smaller pressure in the Dubna experiments. Probably, the neutron counters efficiency has not been evaluated correctly in the Dubna experiments. Our result was confirmed later by the experiments at LAMPF, PSI, and also by new measurements in Dubna.

The precision measurement of $\lambda_{dd\mu}$ was a substantial step in investigation of the muon catalyzed fusion: since then the quantitative comparison between the theory and the experiment became possible. In this respect measurements of the temperature dependence of $\lambda_{dd\mu}(T)$ with precise fixation of the temperature (± 0.3 K) are particularly informative. Such measurements were carried out by our group in 1987 [5]. In Fig. 4 our results are compared with the theoretical calculations of $\lambda_{dd\mu}(T)$ made by the L.I.Ponomarev's group. These calculations use a great number of matrix elements describing the transitions inside the mesomolecular complex. But the final result is mostly sensitive to only two parameters: the energy of the least bound state, ε_{11}, and the fusion probability of the deuterons inside the $dd\mu$ molecule,λ_f. Fig. 4 compares the calculated dependence $\lambda_{dd\mu}(T)$ with the experimentally measured one.The agreement is reached with $\varepsilon_{11} = -1.965 \pm 0.001$ eV, this value being very close to the recently calculated $(\varepsilon_{11})^{calc} = -1.9653$ eV.

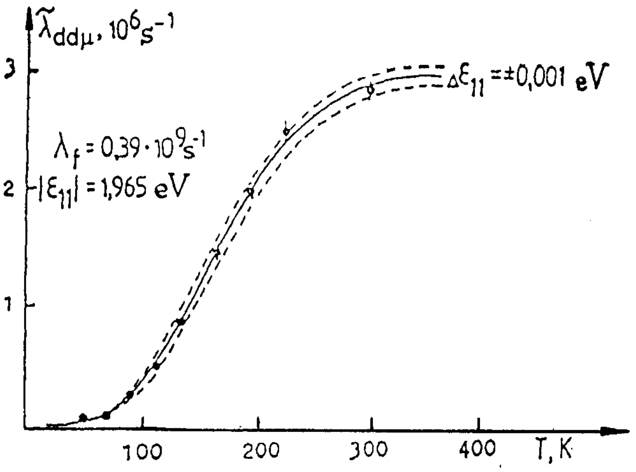

Fig. 4. Resonant dependence of the μCF rate on temperature. Points are the results of our experiment (Gatchina, 1987–1990). The curve is the result of calculations with $|\ \varepsilon_{11}\ | = 1.965$ eV and $\lambda_f = 0.39 \cdot 10^9$ s^{-1}. The dashed lines correspond to variation of ε_{11} within $\Delta\varepsilon_{11} = \pm 0.001$ eV.

The $d\mu$ atom may be formed in two spin states, $F = 3/2$ and $F = 1/2$. The $dd\mu$ molecule formation rates from these states ($\lambda_{3/2}$ and $\lambda_{1/2}$) are different. Soon after formation of the $d\mu$ atoms the $F = 3/2$ state is transferred into the $F = 1/2$ state with the rate $\lambda_{3/2,1/2}$, and the thermodynamic equilibrium occurs. Up to now we discussed the $dd\mu$ molecules formation rate in the equilibrium state. In the PSI experiment the IC was operated in coincidence with the neutron detector thus enabling registration of the dd-fusion events immediately after the moment of the muon stop. The advantage of this experiment in comparison with the previous ones utilizing neutron detectors only was the lower background level and the opportunity to calibrate the neutron detector efficiency with the accuracy of $\pm 1\%$ (compared to $\pm 10\%$ in the previous experiments). As a result, high precision measurements of $\lambda_{3/2}(T)$, $\lambda_{1/2}(T)$, and $\lambda_{3/2,1/2}(T)$ have been performed; the obtained results are presented in Fig. 5.

A detailed theoretical analysis is still to be done after completing our data processing. We only want to mention here the serious discrepancy between the predicted and the experimental values of the spin transition rate $\lambda_{3/2,1/2}$.

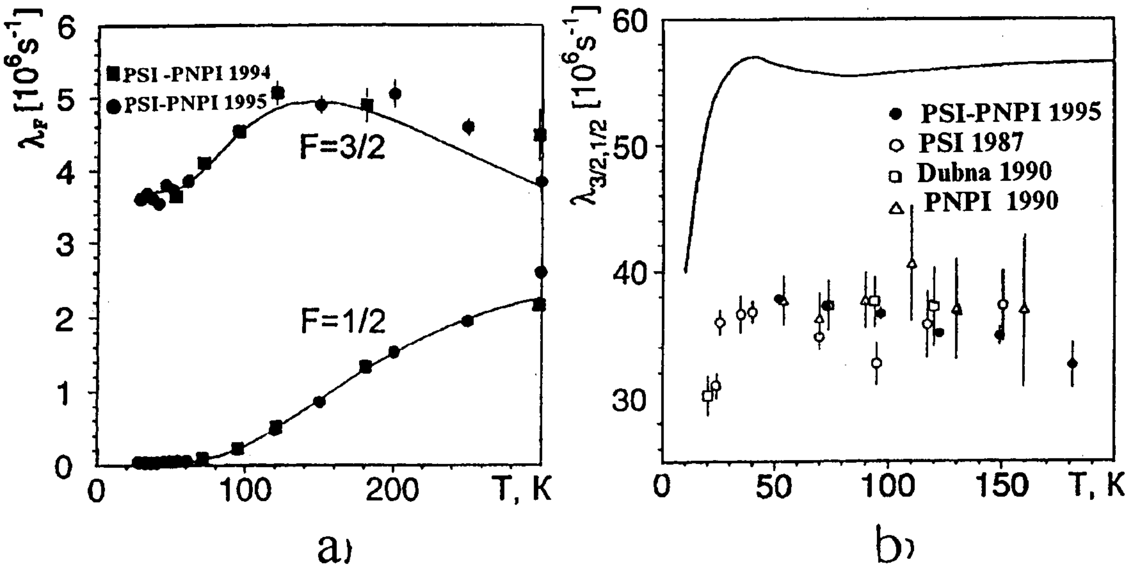

Fig. 5. Temperature dependence:
a) of the $dd\mu$ molecule formation rate in deuterium from two spin states of the $d\mu$ atom;
b) of the spin flip rate in the dμ atom.
Shown by solid lines are results of theoretical calculations.

Muon sticking to helium

Fig. 6 illustrates our method of measuring the sticking probability ω_{dd}. The value of ω_{dd}=0.122±0.003 obtained in our experiment is up to now the only result of direct measurement of this parameter, and it is used to control the accuracy of theoretical calculations.

Before publication of our experimental result, the existed calculated values for the sticking probability were somewhat higher: $\omega_{dd}^{calc} = 0.147$. This discrepancy stimulated the L.Ponomarev's group to carry out new calculations. An attempt to take into account the exited states of the ^{3}Heμ atom just enlarged the discrepancy: $\omega_{dd}^{calc} = 0.165$. Afterwards, the calculations were repeated using more precise wave functions for the $dd\mu$ molecule. The obtained value $\omega_{dd}^{calc} = 0.122$ was in a full agreement with our experiment. A similar revision of the calculation method for the muon sticking probability in $d\mu t$-fusion gave $\omega_{dt}^{calc} = 0.0059$ (instead of the previous value $\omega_{dt}^{calc} = 0.009$). The new value of ω_{dt}^{calc} corresponds to the limiting number of fusions per muon equal to 170.

The isotopic asymmetry in $d\mu d$-fusion

The observed in our experiments difference in the yields of the isotopically symmetric channels

$$R = Y(^3\mathrm{He} + n)/Y(^3\mathrm{H} + p) = 1.39 \pm 0.03$$

still has no firm theoretical explanation. There is an interesting correlation of this result with the conclusions from the phase shift analysis of dd-scattering at the energies from 30 keV to 400 keV. The similar asymmetry was found there in the P wave, while in the S wave $R \approx 1$. In the case of the resonant formation of the $dd\mu$ molecule at T = 300 K the dd-fusion occurs

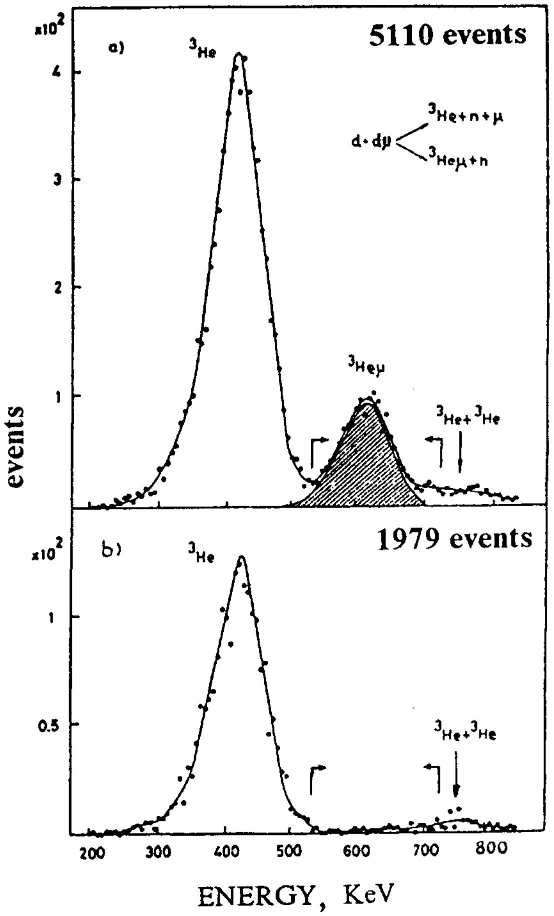

Fig. 6. The direct way of measuring the sticking probability ω_{dd}.
a) The spectrum of all first dd-fusion events.
b) The spectrum of the first fusion events under condition they are followed by another fusion. In this case there are no events with muon sticking (^{3}Heμ) (Gatchina, 1981).

in the pure P state. And on the contrary, for the non-resonant $dd\mu$ molecule formation the dd-fusion must take place in the S state. Thus we should expect that the ratio R will approach $R = 1$ with decreasing the temperature when the resonant mechanism will be changing to the non-resonant one. And that was exactly what we observed in our experiment (Fig. 7.).

This observation has a practical application: one can determine the relative contributions of the resonant and non-resonant channels by measuring the ratio R.

Study of $d\mu d$- and $p\mu d$-fusion in HD mixtures

These studies were aimed at detailed investigation of the $d\mu d$-fusion in the HD molecules [6]. In this case the non-resonant mechanism dominates in the production of the $dd\mu$ molecule thus enabling us to study this mechanism. Also, the measurement of the spin flip rate $\lambda_{3/2,1/2}$ in the absence of the resonant $dd\mu$ molecule formation may help to observe directly the back decay of the $dd\mu$ molecule which is of special interest. This experiment required two technical problems to be solved. Firstly, the mixture with the minimum content of D_2 should be prepared. Secondly, the materials inside the IC should be chosen such to exclude a fast conversion of the H_2/D_2 mixture into the equilibrium state. The first task was successfully fulfilled by our chemists who developed a method for production of pure HD gas with the D_2 content on a level of less than 2%. The second problem was solved by excluding from the construction materials nickel that catalyzed the equilibration process in the H_2/D_2 mixture. First measurements in the mixture HD + D_2(2%) at T = 300 K, 150 K, and 50 K were carried out at PSI in the

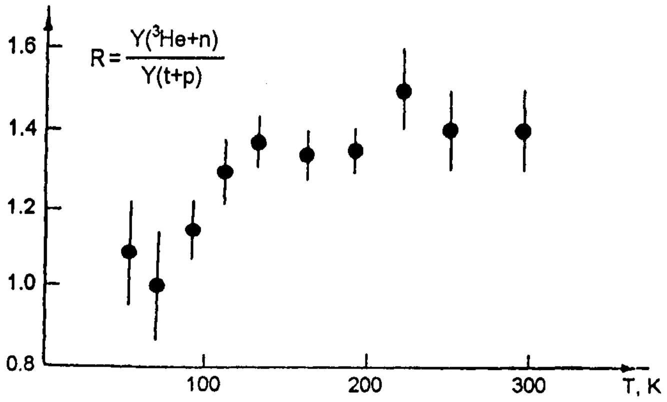

Fig. 7. Temperature dependence of the relative yields of the isotopically symmetric channels in *dd*-fusion (Gatchina, 1987–1990).

beginning of 1996. The preliminary result was:

$$\lambda_{dd\mu-HD} = (0.115 \pm 0.004) \cdot 10^6 \text{ s}^{-1} \ (T = 300 \text{ K}), \ \lambda_{3/2,1/2} = (28 \pm 5) \cdot 10^6 \text{ s}^{-1} \ (T = 50 \text{ K}).$$

The obtained value of $\lambda_{3/2,1/2}$ was significantly lower than that measured in the D_2 gas thus pointing on essential contribution of the $dd\mu$ molecule back decay to the spin flip rate in the case of the muon stop in the D_2 gas.

The exceptionally low value of $\lambda_{dd\mu-HD}$ favours utilization of the HD filling in the situations which require suppression of the $d\mu d$-fusion background. In particular, this enables study of the $p\mu d$-fusion on a qualitatively new level by measuring the absolute yields of the two reaction channels:

$$d\mu + p \rightarrow pd\mu \rightarrow {}^3\text{He} + \mu; \qquad \rightarrow {}^3\text{He}\,\mu + \gamma \rightarrow {}^3\text{H} + \tilde{\nu}_\mu + \gamma. \qquad (2a,2b)$$

The measured amplitude spectrum is shown in Fig. 8.

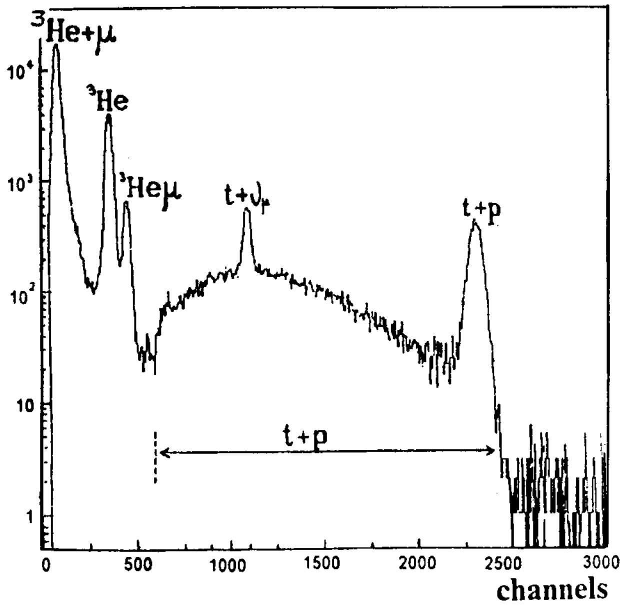

Fig. 8. Amplitude distribution of the $p\mu d$- and $d\mu d$-fusion signals in the HD filled IC (PSI-PNPI, 1996). The (^{3}He+μ) events correspond to the muon conversion reaction (2a). The $(t + \nu_\mu)$ events are the products of the muon capture in the channel (2b). The ^{3}He (^{3}Heμ) events, as well as the $(t + p)$ events are the products of the *dd*-fusion.

The data analysis should allow us to determine the dependence of $\lambda_{pd\mu}$ on the temperature and on the H/D mixture composition. Also, it makes possible determination of the nuclear fusion rate in different spin states of the $pd\mu$ molecules: $\lambda_f^{3/2}$ and $\lambda_f^{1/2}$.

Another example of utilization of the HD filling is a search for the $d\mu{}^3$He-fusion following formation of the d^3Heμ molecule:

$$^3\mathrm{He} + d\mu \rightarrow {}^3\mathrm{He}\ d\mu \rightarrow {}^4\mathrm{He} + p + \mu. \tag{3}$$

Our first measurements at Gatchina set the upper limit [7]:

$$\lambda_f \leq 4.10^8\ \mathrm{s}^{-1}.$$

The new data from the 1996 run at PSI should allow to lower this limit by at least two orders of magnitude. The data analysis is in progress.

Muon transfer to helium

We performed the first measurements of the muon transfer rates from the ground state of the $d\mu$ atoms to ^{3}He and ^{4}He. The experimental method was based on observing the changes in the $d\mu d$-fusion rate while adding the controlled amount (2–5%) of helium to D_2 gas. The following results were obtained [8]:

$$\lambda_{d^3He} = (1.27 \pm 0.10) \cdot 10^8\ \mathrm{s}^{-1}, \qquad \lambda_{d^4He} = (3.68 \pm 0.18) \cdot 10^8\ \mathrm{s}^{-1}.$$

These results confirmed the hypothesis of the new mechanism of the muon transfer to He nuclei via formation of the dHeμ molecules formulated by N.P.Popov in 1981. The muon transfer rate in this case proved to be 100 times higher than the rate predicted by the direct transfer mechanism. A practical consequence of this observation is the necessity of periodical purification of the D/T mixture from the helium accumulated in the future mesocatalitic reactors.

Study of $d\mu t$-fusion

The $d\mu t$-fusion is of special interest because this reaction is considered to be a potential source of neutrons and energy. The main task of our first experiments with the D/T mixture (Gatchina, 1987) was to study a behaviour of the IC under conditions of the tritium background. A special multi-anode chamber was designed and the necessary technological equipment for operation with tritium was constructed. The chamber was filled with the D_2 + T_2(~1%) mixture at 90 atm pressure. In this mixture the following sequence of reactions should occur:

$$d\mu \rightarrow t\mu \rightarrow dt\mu \rightarrow {}^4\mathrm{He} + n + \mu; \qquad \rightarrow {}^4\mathrm{He}\mu + n. \tag{4a,4b}$$

The experiment was performed at room temperature. The muon transfer rate from the ground state of the $d\mu$ atom to the $t\mu$ atom was measured [9]: $\lambda_{dt} = (2.8 \pm 0.2) \cdot 10^8\ \mathrm{s}^{-1}$. The measured value was in a good agreement with the theory and with the previous results.

After formation of the $t\mu$ atom, the $dt\mu$ molecule formation was so fast in the D/T mixture used in the experiment that it was impossible to measure the rate $\lambda_{dt\mu}$. Therefore in the further experiments the D/T mixture was diluted with hydrogen: H_2(78%) + D_2(20%) + T_2(2%). This mixture was converted into the equilibrium state so that the HD molecules dominated over the D_2 molecules (D_2 – 5.8%, HD – 32.8%). This triple H/D/T mixture proved to be very convenient for our purposes. Without reducing the number of muon stops, as well as the $dt\mu$-fusion yield, it changed the time distribution of the fusion events in such a way that it became possible to measure the $dt\mu$ molecules formation rates in D_2 and HD complexes. Finally we obtained [9]:

$$\lambda_{dt\mu-D_2} = (2.1\pm0.6)\cdot10^8 \text{ s}^{-1}, \qquad \lambda_{dt\mu-HD} = (1.3\pm0.3)\cdot10^8 \text{ s}^{-1}.$$

Besides, in the triple mixture (especially in the equilibrium state) the background from the $d\mu d$-fusion decreased drastically that was very important for us to achieve our main goal – the direct determination of the probability of muon sticking to ^{4}He, ω_{dt}.

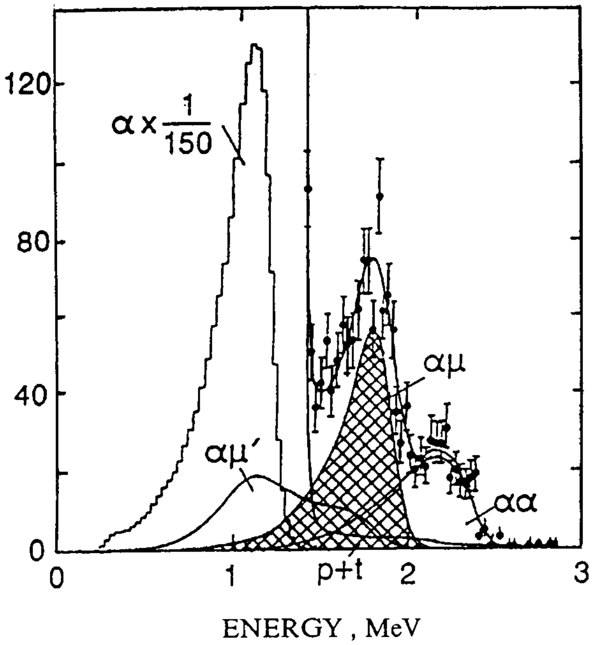

Fig. 9. Amplitude distribution of dt-fusion events registered with the IC. The shaded area corresponds to the events with $\alpha\mu$ sticking. The $(\alpha\mu\prime)$ events originate from muon shaking off during the slowing down of the $\alpha\mu$ atoms in the gas. The $(\alpha\alpha)$ events are the pileups with the signals from the subsequent fusions (PSI–PNPI, 1988–1992).

The experiment on ω_{dt} determination was carried out at PSI in the period from 1988 to 1992 [10]. The method was similar to that used for ω_{dd} determination: the utilization of the recombination effect for the separation of the $(^4\text{He})^{++}$ and $(^4\text{He}\mu)^+$ peaks. But this time we had to measure a very small value, ω_{dt}, and, besides, in the presence of the tritium background and the background from the $(t+p)$ channel of the $d\mu d$-fusion. The latter background was reduced by choosing the triple H/D/T mixture in the equilibrium: $C_t = 0.05\%$, $C_d = 9\%$, and $C_p = 91\%$. Moreover, the coincidence of the chamber signals with the signals of the neutron counters was used to suppress the $(t+p)$ channel. The small tritium concentration allowed to maintain good energy resolution, $\sigma = 80$ keV. The relatively low yield of the dt-fusion events per muon stop ($\sim$2%) was compensated by the high rate of the muon stops ($\sim$1000 s^{-1}) in the chamber sensitive volume (3 cm^3) due to unique properties of the PSI muon channel. As a result, more than $5\cdot10^6$ dt-fusion events were registered, and the muon sticking ^{4}Heμ events were clearly separated (Fig. 9) that made it possible to determine the sticking probability, $\omega_{dt} = (0.56 \pm 0.04)\%$ [11]. This value takes into account the probability of the muon shaking off during the slowing down of $(^4\text{He}\mu)^+$ in the gas. This is the first and so far the only result of direct measurement of ω_{dt}. It is in quite good agreement with the latest calculations. The obtained value of ω_{dt} sets the upper limit on the number of dt-fusions catalyzed by one muon, $Y_n = 180$.

Another important result of the experiment was the observation of the epithermal channel of the $dt\mu$ molecules formation due to interaction of the "hot" $t\mu$ atoms with the HD molecules. In the experiment this fact exhibits itself as the peak in the time distribution of the dt-fusion neutrons (Fig. 10).

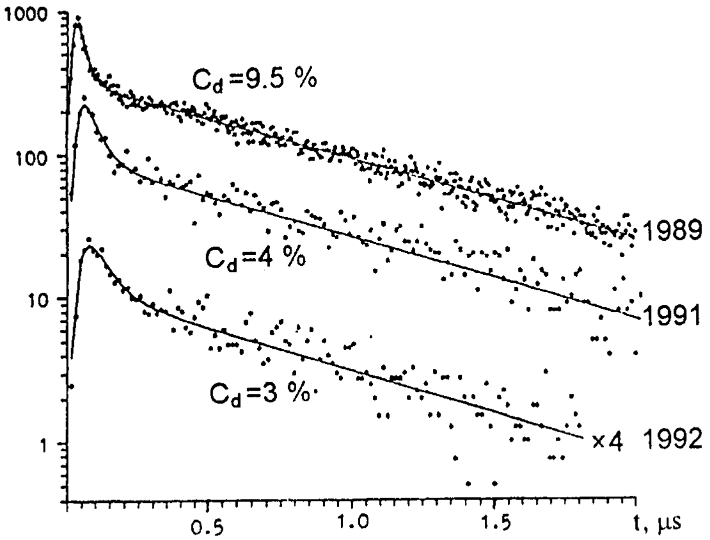

Fig. 10. Time distribution of the neutrons from the dt-fusion reaction in the triple mixture H/D/T. The peaks in the distributions are due to epithermal formation of the $dt\mu$ molecules (PSI–PNPI, 1989–1992).

The analysis of these distributions revealed the extremely high $dt\mu$ molecule formation rate [12]:

$$\lambda^{epitherm}_{dt\mu-HD} = (2.5\pm0.6)\cdot10^{9}\ \mathrm{s}^{-1}.$$

This result agrees with the theoretical calculations predicting the existence of a strong resonance in the dependence of $\lambda_{dt\mu-HD}$ on the $t\mu$ atom energy in the energy range of ≈ 1 eV. Another factor that favours the epithermal formation of the $dt\mu$ molecules is the Ramzauer effect in the $t\mu$-H collisions slowing down the thermalization of the $t\mu$ atoms in the triple H/D/T mixture. We should note the absence of this effect in the D/T mixture.

This observation opens new possibilities for the practical utilization of the $d\mu t$-fusion, for example, in the project of an intensive 14 MeV neutron source.

Conclusions

Presented here results of investigations of the muon catalyzed fusion reactions form the today's data base being used for the comparison with the theory. They illustrate the efficiency of the experimental method developed at PNPI as well as the importance of combining the efforts and potentialities of different laboratories.

The PNPI participants taking part in various stages of development of the experimental method and in carrying out the measurements:
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