EXPERIMENTAL STUDY OF MCF PROCESSES AT DLNP OF JINR

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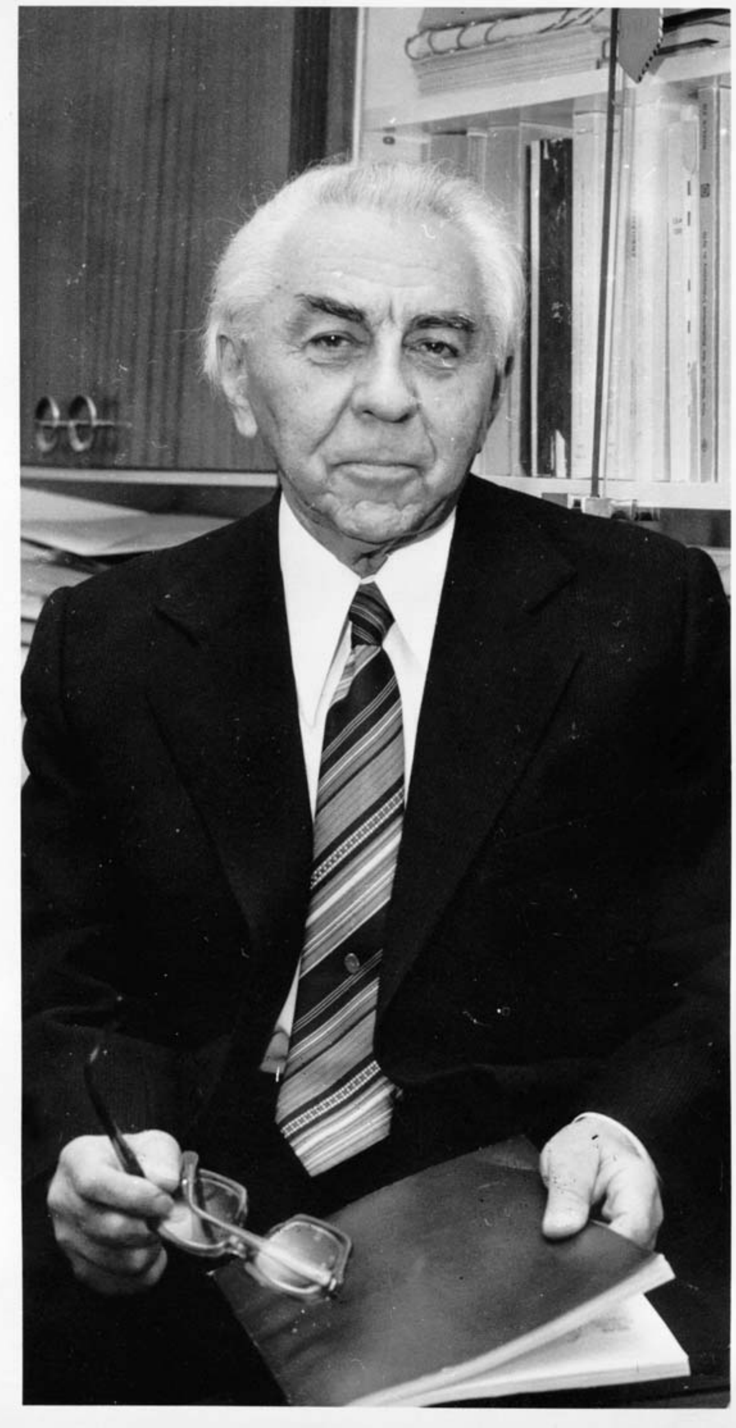
Experimental study of the MCF processes is the traditional direction in the JINR scientific activity. Starting from the beginning of the 60-th it continues till now.

Professor V.P. Dzhelepov
was the initiator and permanent leader of this branch up to his death in 1999.



I. 1962-1966

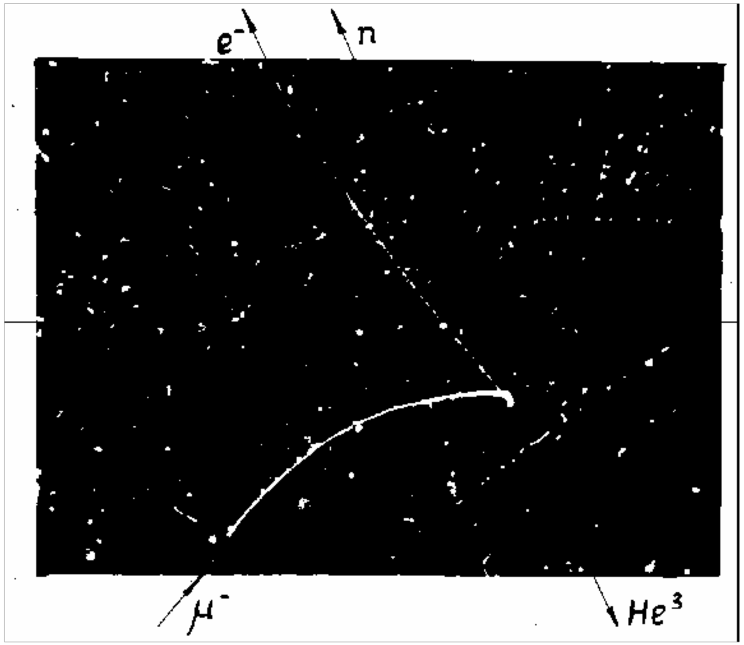
The first, in many aspects pioneering, works were carried out with the DCC, filled with gaseous H2, D2 or their mixture at the pressure from 7 to 20 bar.
P. Ermolov was the generator of the experiment and S.Gerstein was the ideological leader.
The peculiarities of the method made it possible to observe the ranges of neutral mu-atoms and charged products of the fusion reactions.

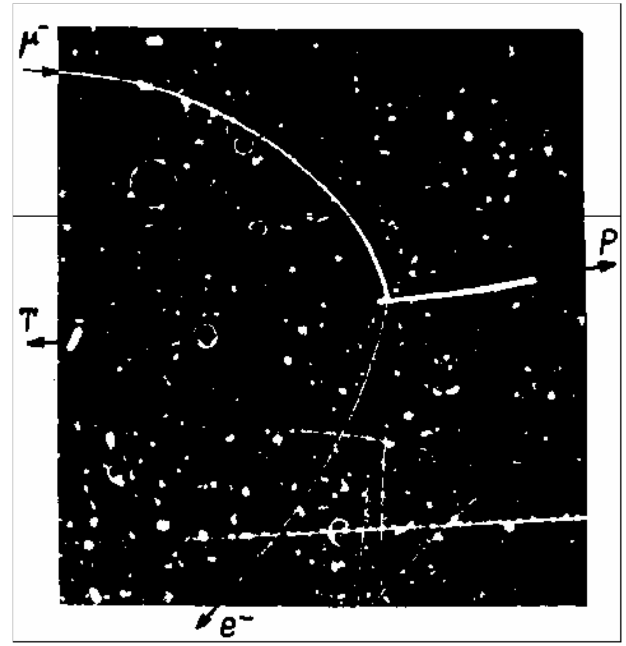
$$d\mu + p \rightarrow pd\mu \rightarrow {}^3He + \gamma + \mu + 5.5\ MeV$$

$$d\mu + d \rightarrow dd\mu \rightarrow t + p + \mu + 2.5\ MeV$$

$$d\mu + d \rightarrow dd\mu \rightarrow {}^3He + n + \mu + 2.5\ MeV$$

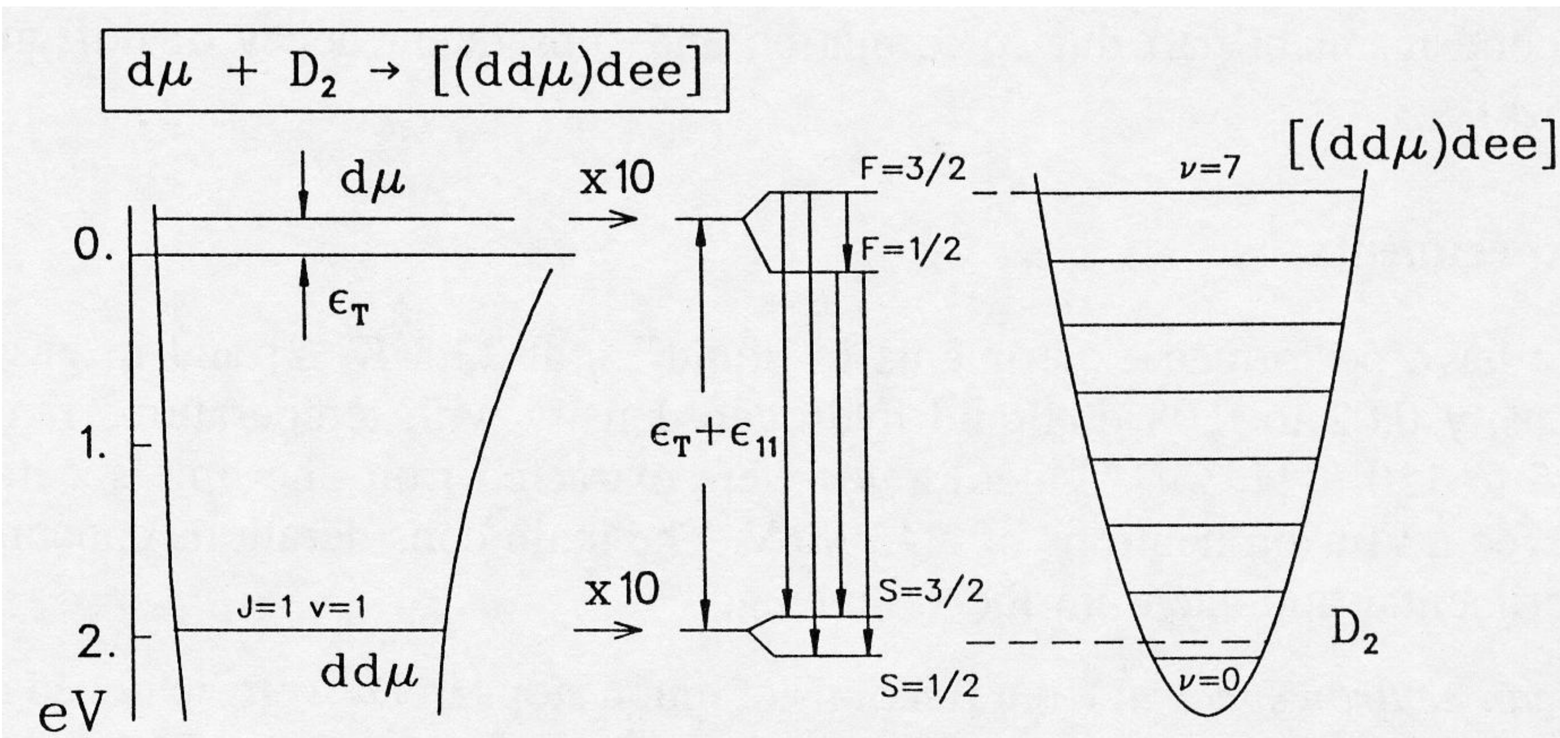
We have estimated the cross sections of $p\mu$- and $d\mu$-atoms scattering on hydrogen, deuterium and complex nuclei, the $pp\mu$-, $pd\mu$-, $dd\mu$-molecule formation rate.


e⁻
n
μ⁻
He³


μ⁻
P
T
e⁻


μ⁻
μ⁻

The most remarkable achievement was the discovery of the resonance mechanism of the ddμ-molecule formation with its theoretical explanation:
S.S.Gerstein, V.P.Dzhelepov, P.F.Ermolov, V.V.Filchenkov, E.A.Vesman; 1966-67.



II.1974-78

Wide experimental program was performed with a counter technique using the high pressure (40 bar) gaseous hydrogen target with the inner scintillator (CsI(Ta)).
The works were made together with V.Petruchin group providing the new system of the data analysis.
Mu-decay electron, gamma (p-d fusion and Xeμ) and d-d fusion neutron were detected.
The ppμ- and pdμ-molecule formation rates were measured and nuclear fusion in pdμ was investigated.
Also the cross sections of pμ-atom scattering on hydrogen and muon transfer rate from pμ to He were determined.

The most remarkable result was direct proof of the Vesman resonance mechanism existence by measuring of the temperature dependence $\lambda_{dd\mu}$ (T).

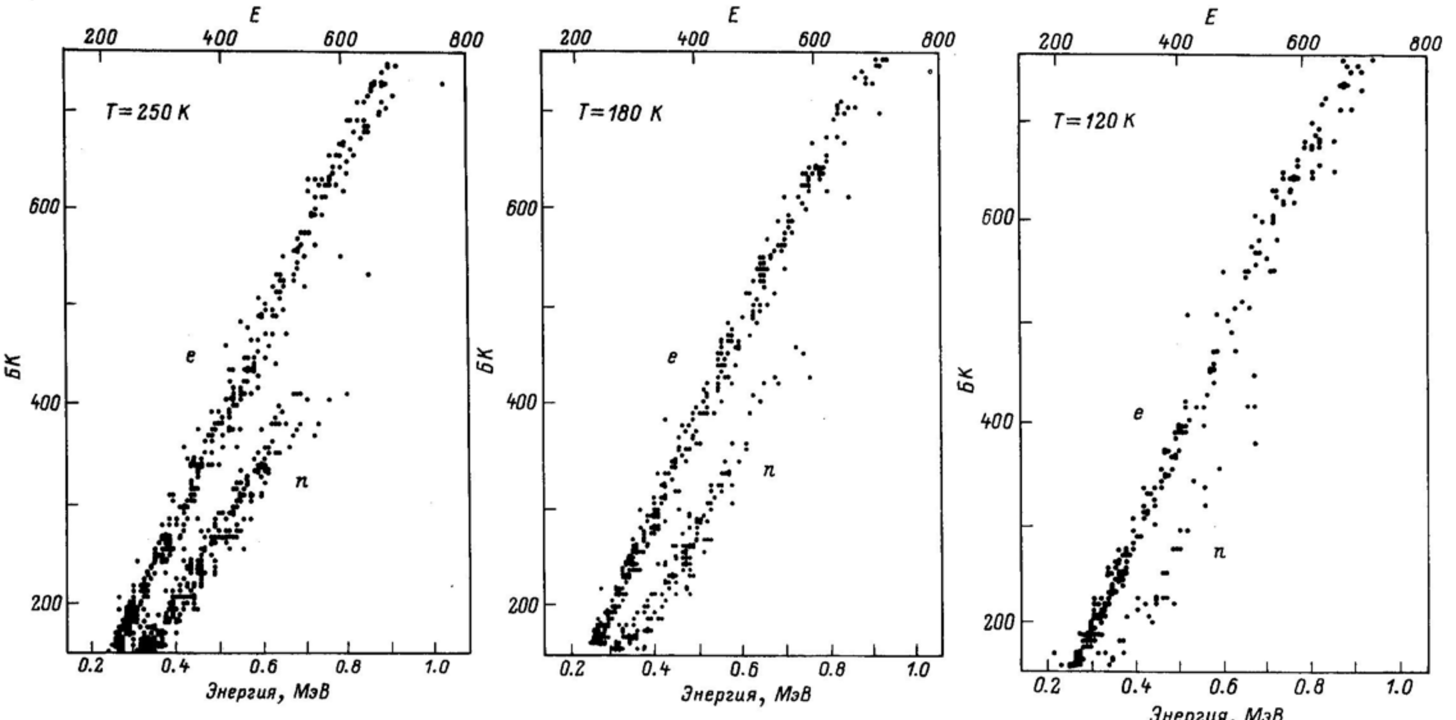
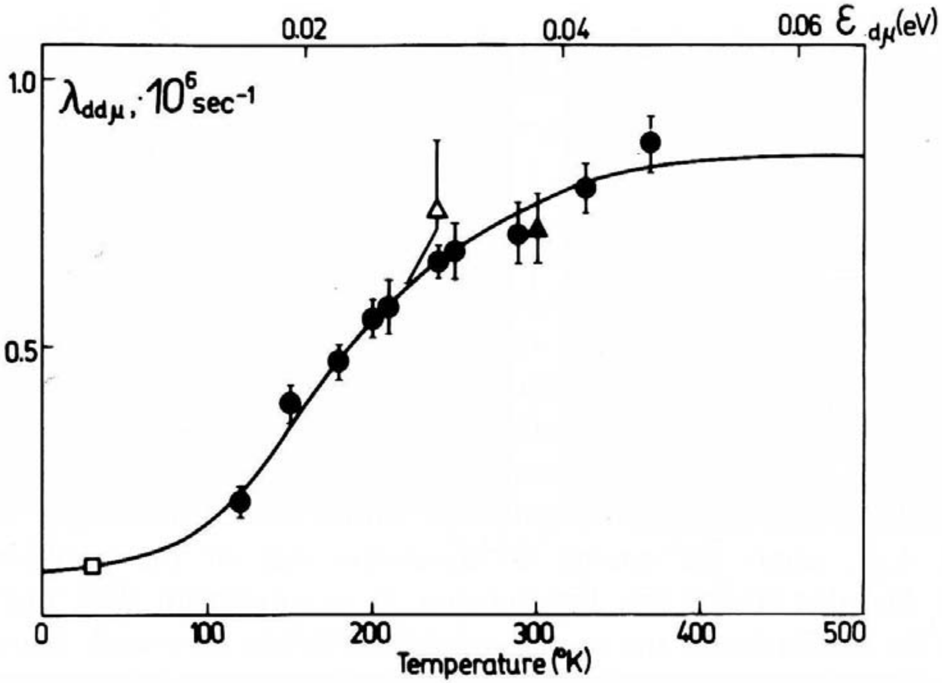


Рис. 3. Распределения, характеризующие разделение нейтронов из реакции $dd\mu \to {}^3\mathrm{He} + n + \mu$ и фоновых γ-квантов и электронов [25]. По осям отложены амплитуды сигналов, пропорциональные интенсивностям двух различных временных компонент E и $БК$, светового импульса нейтронного детектора.



Measured temperature dependence $\lambda_{dd\mu}$ (T).

This result was presented in the Int. Conf. in Zurich in 1977.
[V.P.Dzhelepov, V.M.Bystritsky, V.V.Filchenkov et al., Proc. of VII Int. Conf. on High Energy Physics and Nuclear Structure, Aug. 28 - Sept. 3, 1977, Zurich. Ed. M. Locher, Plenum Press, Basel, 1977; JETP 49, 232 (1979).]

At the same Conference L.I.Ponomarev reported on the Dubna results of the calculations of muonic molecules levels.
[L.I.Ponomarev, Proc. of VII Int. Conf. on High Energy Physics and Nuclear Structure, Zurich, 403 (1977).]

So **1977** can be considered as a key point in the MCF history.

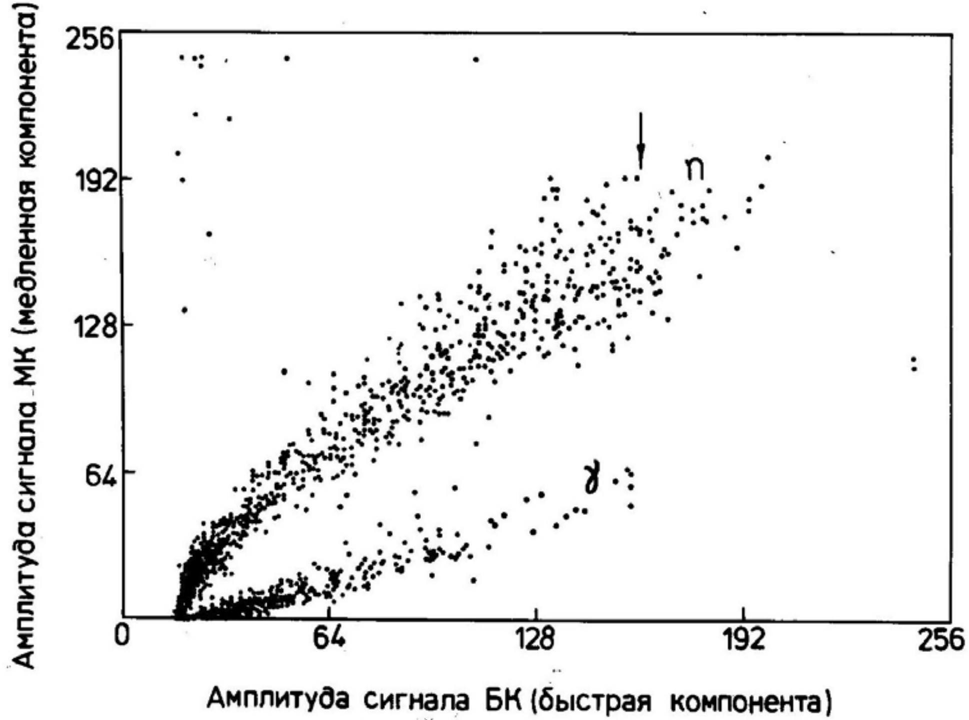
Reliable determination by L.I. Ponomarev and I.V.Puzynin groups of the weakly bound level in ddμ, responsible for the resonance and their prediction on much more intensive resonance for dtμ formation together with experimental results for λddμ (T) gave the power stimulus for the intensive MCF investigations in the world.

After 1977 it would be very important to try to detect the muon catalyzed d+t fusion in D/T mixture

$$\mathbf{t\mu + d \rightarrow dt\mu \rightarrow {}^{4}He + n + \mu + 17.6\ MeV}$$

and check the theoretical prediction on very intensive resonance in the dtμ-molecule formation resulting in producing more than 100 neutrons and more than 2 GeV energy releasing by one muon. The Dubna group was the first to experimentally investigate the muon catalyzed d-t fusion and to confirm the theoretical predictions of the high intensity of this process.

Professor V.G. Zinov was the generator of the experiment.



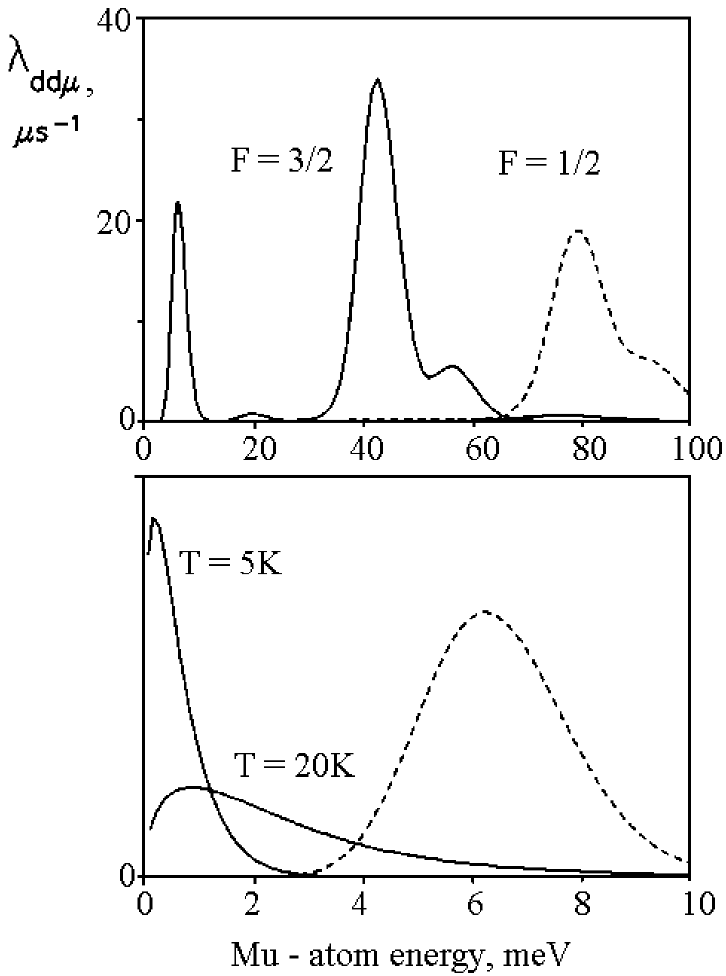
The investigated process was clearly identified and its main parameters were determined:

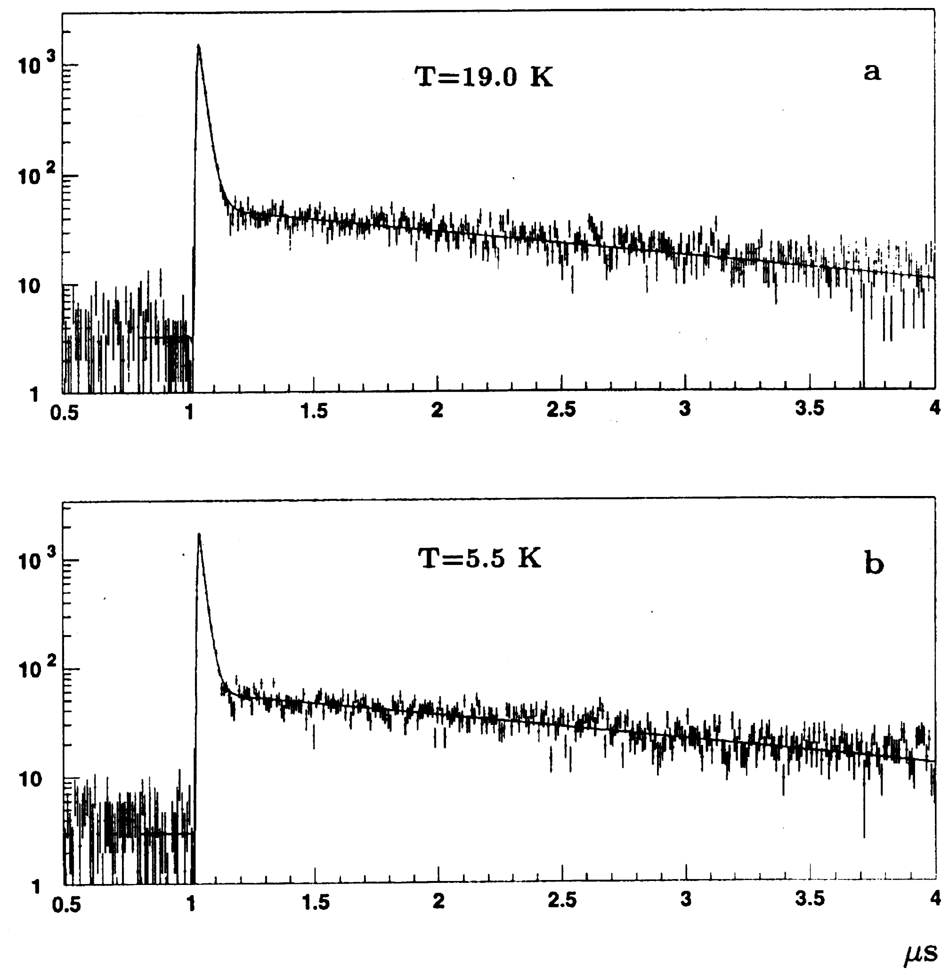
$$\lambda_{dt\mu} > 10^8 \ s^{-1}, \qquad \lambda_{dt} = (2.9 \pm 0.4) * 10^8 \ s^{-1}$$

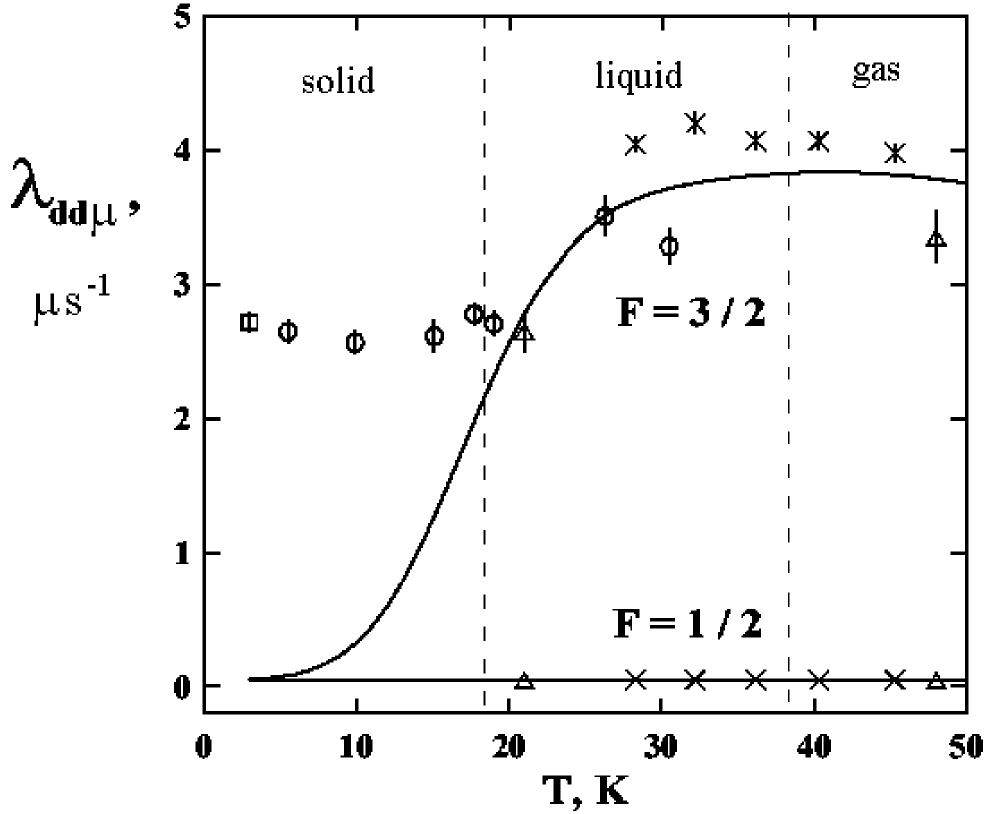
V.P.Dzelepov, V.G.Zinov, V.M.Bystritsky, V.V.Filchenkov et al., Phys. Lett. B 94 (1980) 476; Zh.Exp. Teor. Fiz. 80 (1981) 1700.

III. 1987-95

ddμ-molecular formation from the different dμ-atom spin states in solid, liquid and gaseous deuterium







Dependence of the ddμ-molecule formation rate from the dμ-atom spin state with F=3/2;1/2 on temperature

D.L.Demin et al., Hyperfine Interact. 101/102 (1996) 13.

P.E.Knowles et al., Hyperfine Interact. 101/102 (1996) 21.

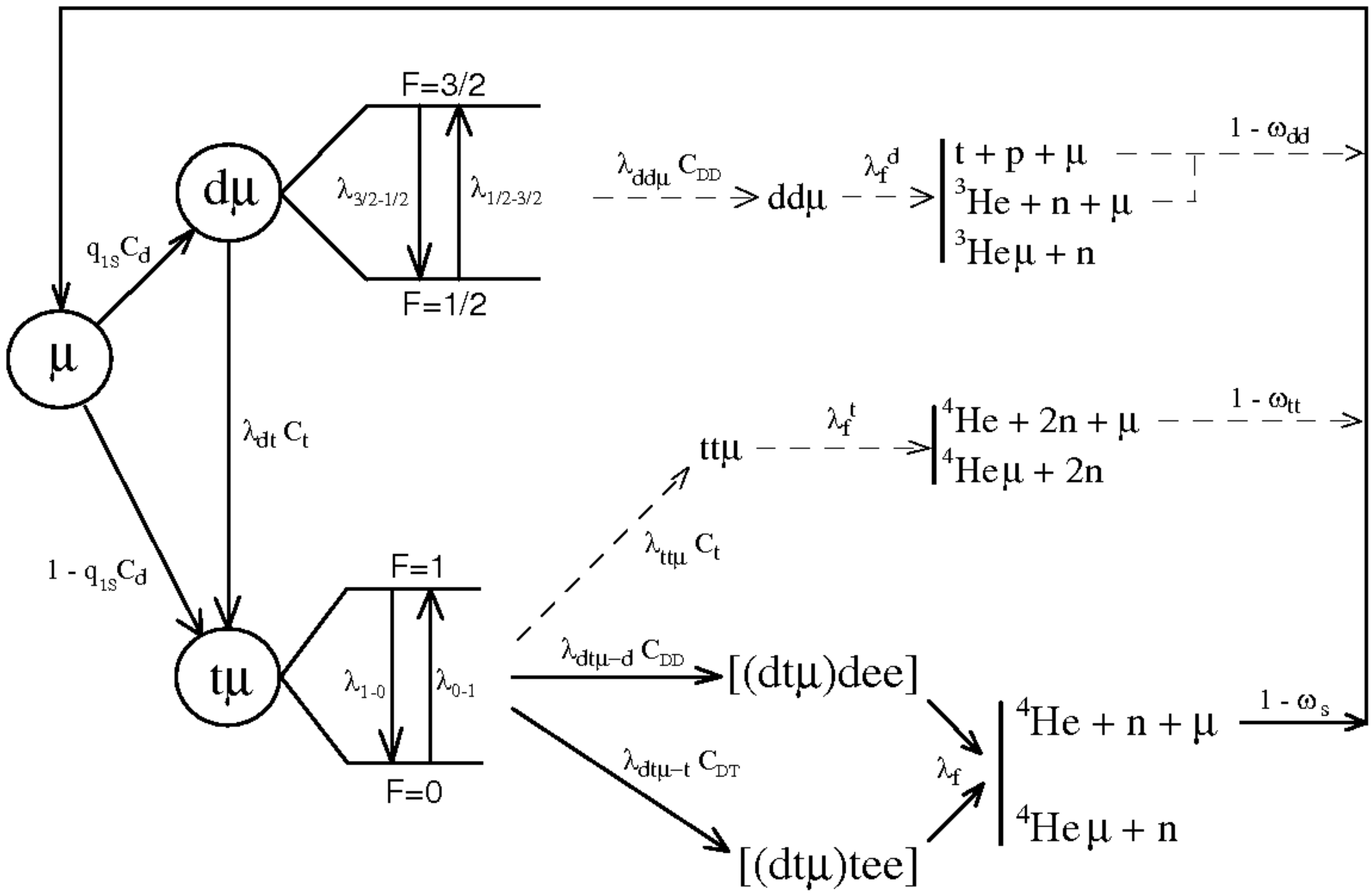
IV. Since 1995

Modern history for the MCF experimental study in Dubna is marked, first of all, by participation in it of the Sarov (RFNC-VNIIEF) team (leader A.A.Yukhimchuk). RFNC-VNIIEF and JINR developed the facility TRITON aimed for systematic study of the MCF processes in D/T and H/D/T mixtures

$$t\mu + d \rightarrow dt\mu - p,d,t \rightarrow {}^4He + n + \mu + 17.6\ MeV$$

in wide experimental conditions.

V.R.Bom et al., JETP 100, No.4 (2005) 663.



Scheme of the MCF processes

in the double D/T mixture

Installation “Triton”

The principal feature of the method are:

1. Use of the unique tritium gas handling system and the targets of original construction which made possible to carry out the investigations in the record wide region in temperature: T=20 K - 800 K and mixture density: φ=0.1 - 1.2 LHD.

2. Employment of the high efficiency neutron detection system based on FANS. These points provided the high measured neutron yield Yn per muon (tens).

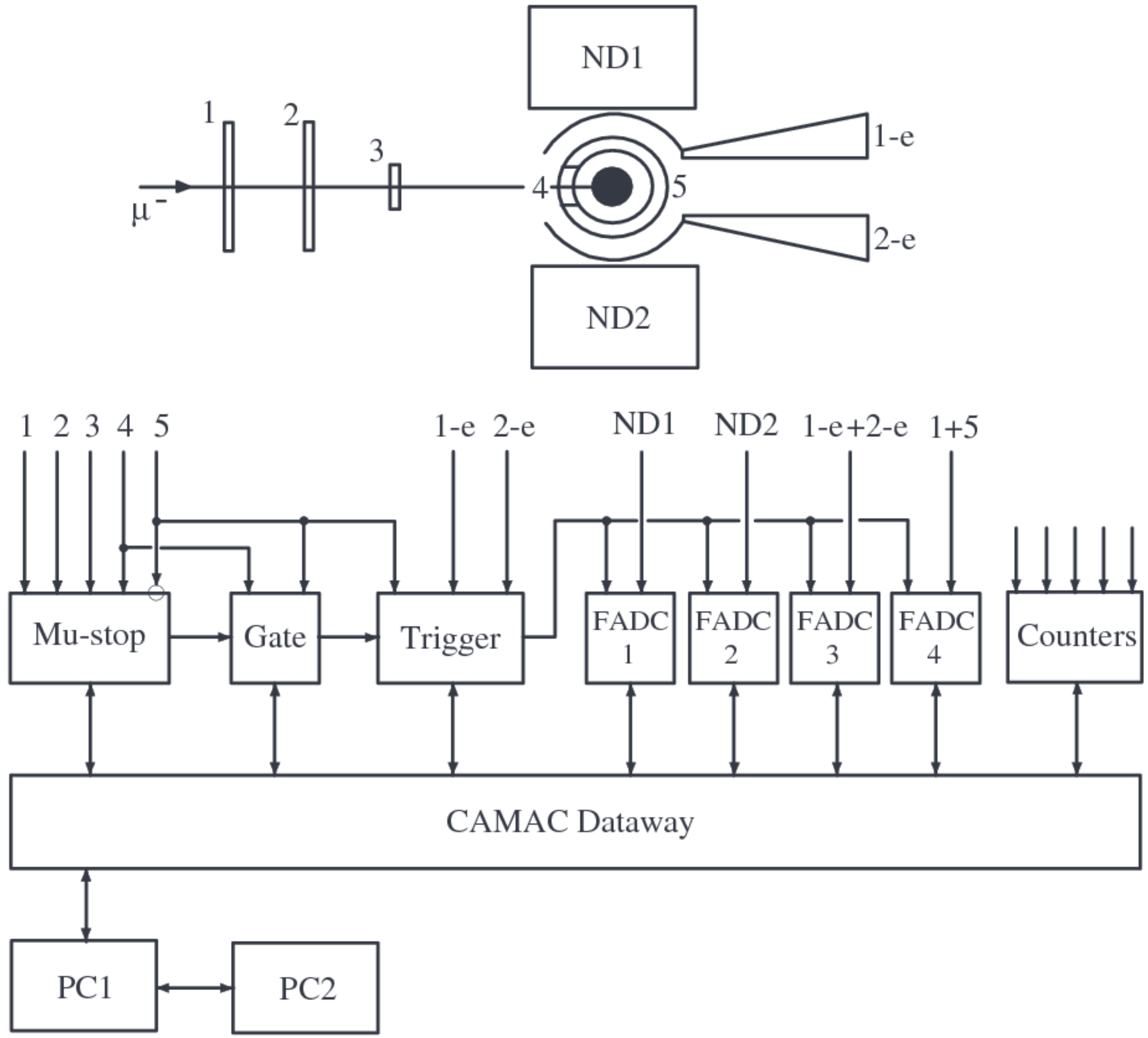
3. The charge distributions for the ND signals were measured (FADC), contrary to the usually registered ones of number of events. This allowed us to eliminate the pileup problem and manage the high neutron yield.

4. It is principally important the use of the novel analysis methods developed by the authors. This made possible to directly determined the "effective" MCF parameters:

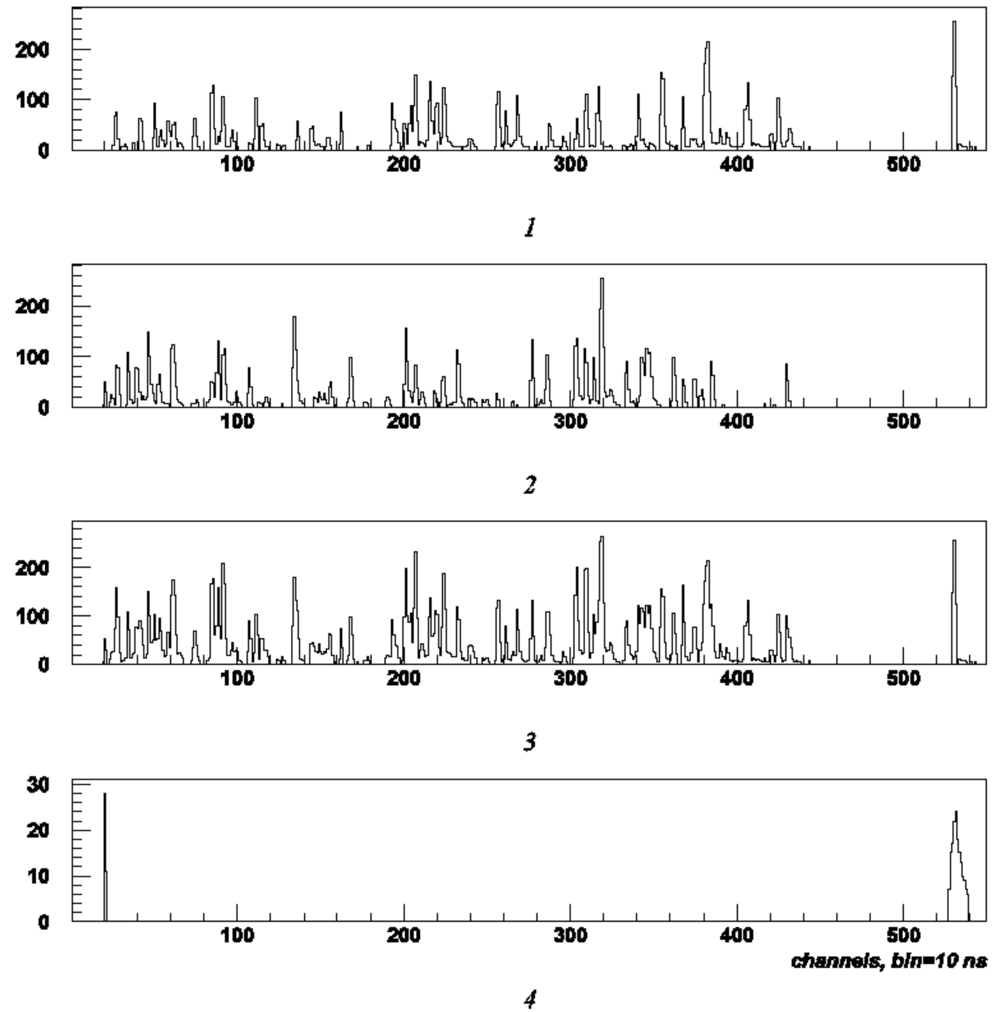
$*$ cycling rate $\boldsymbol{\lambda_c}$,

$*$ the effective muon losses **W** (mainly ω_s) contrary to the other groups where only their product was measured.

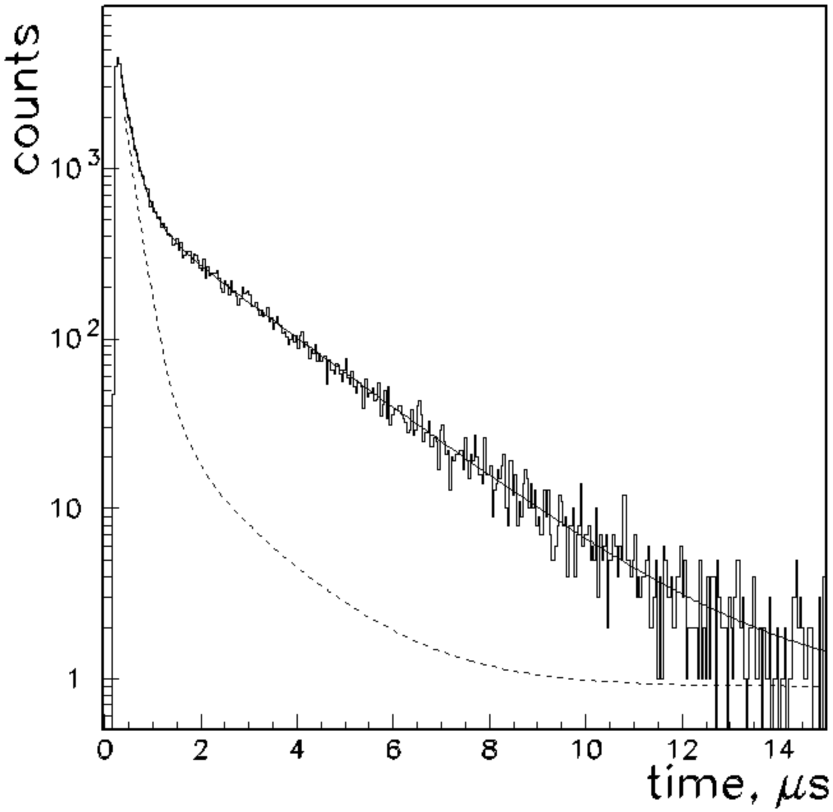
Application of these methods (which where named as "te - tn" and "multiplicity“) allowed us to avoid, in principle, the systematic errors (false electrons) and to essentially improve the quality of the results.

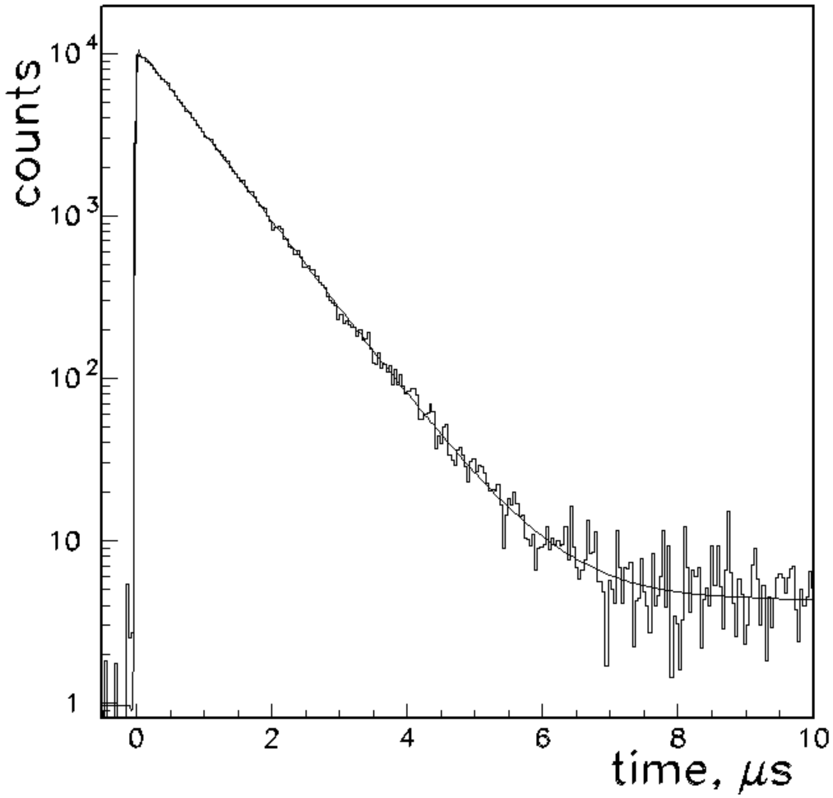


Experimental layout



Flash ADC signals for a single muon





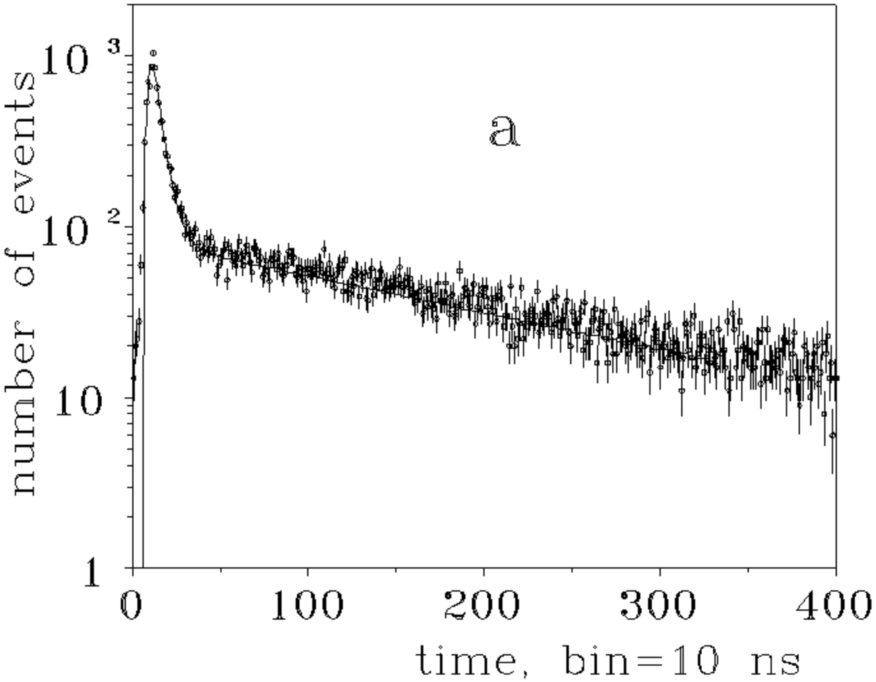
“Standard” method.

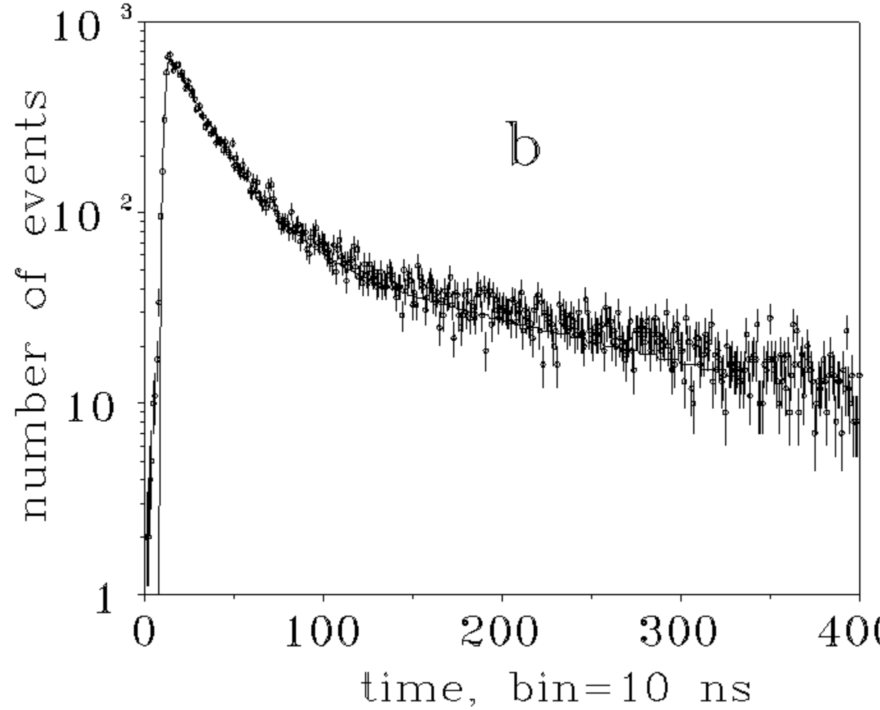
Left – electron time distribution. Dashed line is electrons from empty target

Right – time distribution of neutrons from d+t reacion

$$\frac{dN_n}{dt} = N_\mu \epsilon_n \Lambda_c \exp(-\lambda_n t), \quad \lambda_n = \lambda_0 + w\Lambda_c$$

$$\Lambda_c = \lambda_c \varphi$$





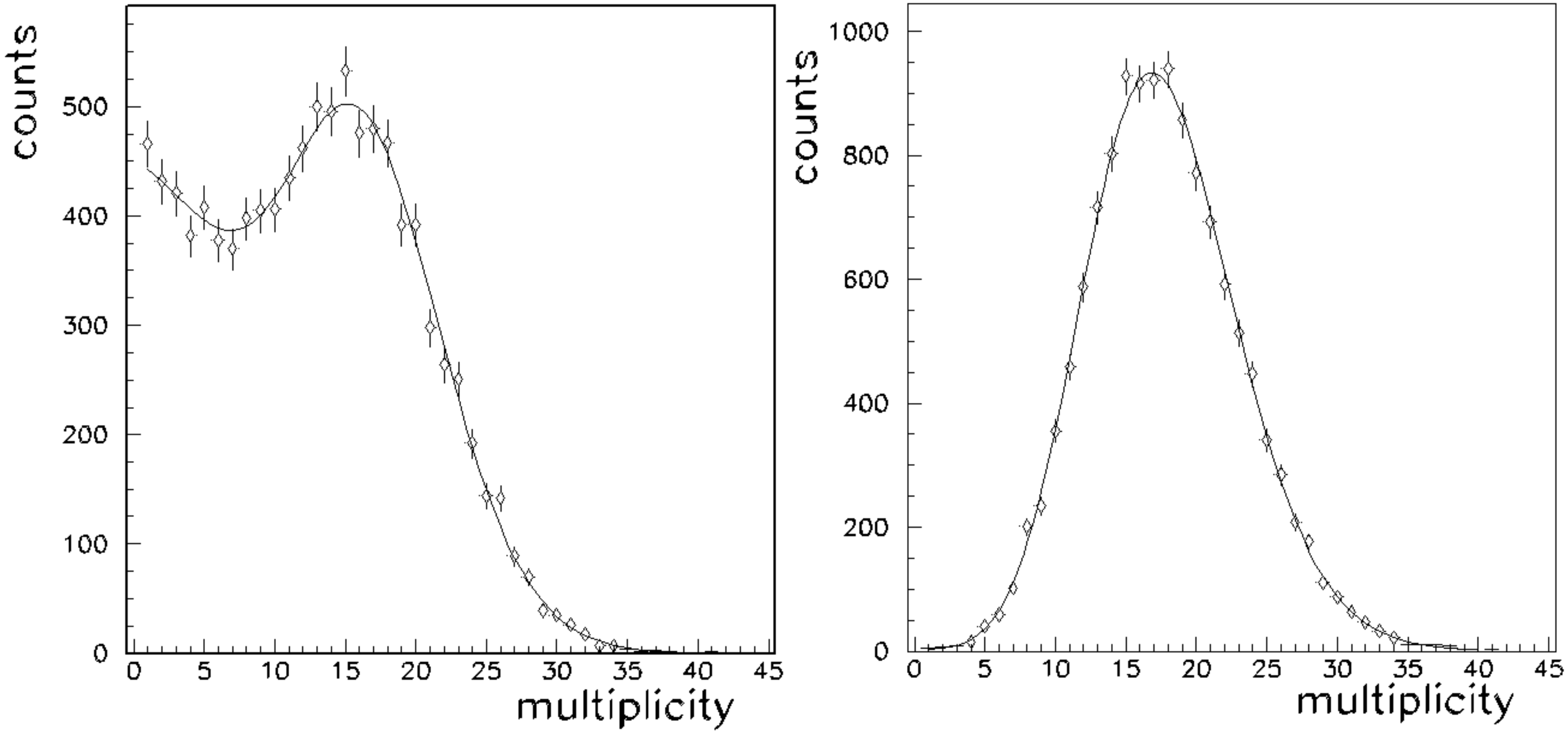
Electron – last neutron (“te-tn”) method.

a – spectrum for exposure with mixture with tritium concentration Ct=35 %

b – spectrum for exposure with mixture with tritium concentration Ct=85 %

$$\frac{dN_{ne}}{dt} = \frac{\lambda_0}{\lambda_n} \times [\omega\Lambda_c \exp(-\lambda_0 t) + \epsilon_n \Lambda_c (1-\omega) \exp(-(\lambda_0+\lambda_n)t)$$

$$\lambda_n = (\epsilon_n + \omega - \epsilon_n\omega)\Lambda_c$$



“Multiplicity” method. Left – distribution with sticking events

Right – distribution without sticking events

$$f(k) = \frac{[\epsilon_n(1-\omega)]^k}{(\epsilon_n+\omega-\epsilon_n\omega)^k}P(k) + \frac{[\epsilon_n(1-\omega)]^{k-1}\omega}{(\epsilon_n+\omega-\epsilon_n\omega)^k}F(k)$$

$$P(m) = \frac{(\lambda_n T)^k}{k!}e^{-\lambda_n T} \qquad F(k) = 1 - e^{-\lambda_n T}\sum_{i=0}^{k-1}\frac{(\lambda_n T)^i}{i!} \qquad m = \lambda_n T$$

Collaboration

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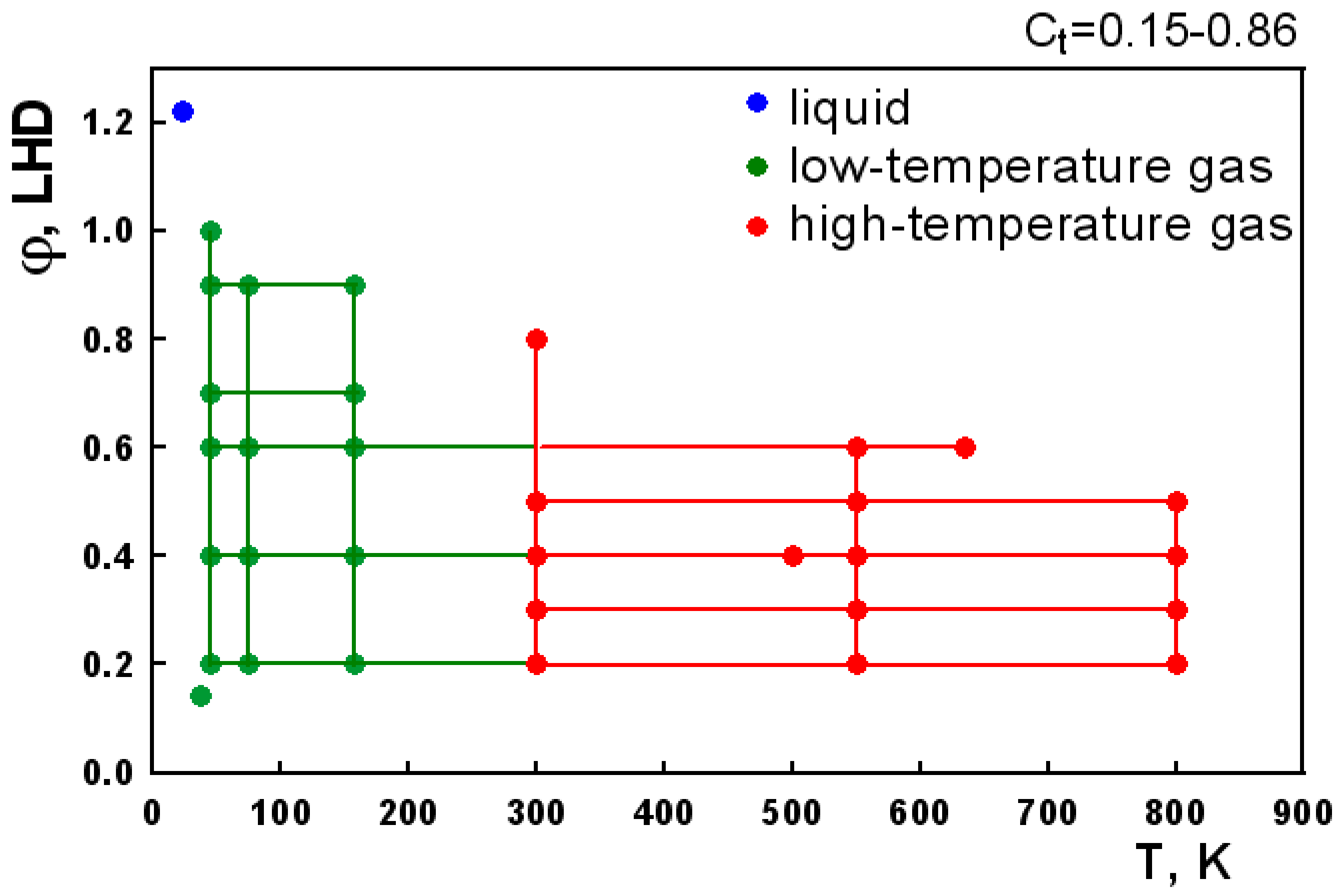


The experimental conditions (density and temperature) for the MCF process study in the D/T mixtures

A serious study of the D/T MCF processes was performed at PSI: gas, liquid, solid

$\varphi \approx 0.01$ LHD, $T = 12 – 300$ K

$\varphi = (0.01 – 1.45)$ LHD, $T = 12 – 40$ K

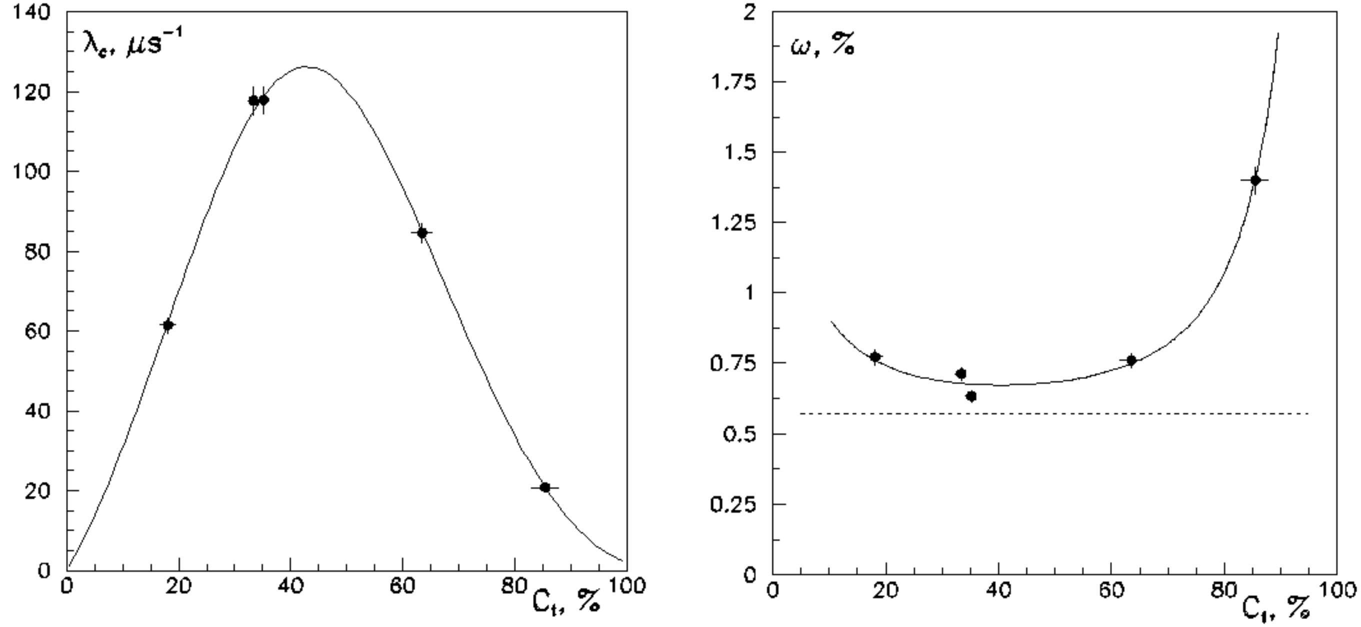
RIKEN-RAL: liquid, solid

TRIUMF: solid.

The only group that investigated MCF in the high-density ($\varphi \sim 1$ LHD), high-temperature ($T \leq 600$ K) D/T mixtures was the LAMPF team.

But its measurements had a hasty character and caused several questions on the analysis.

Results for the experiment with liquid D/T



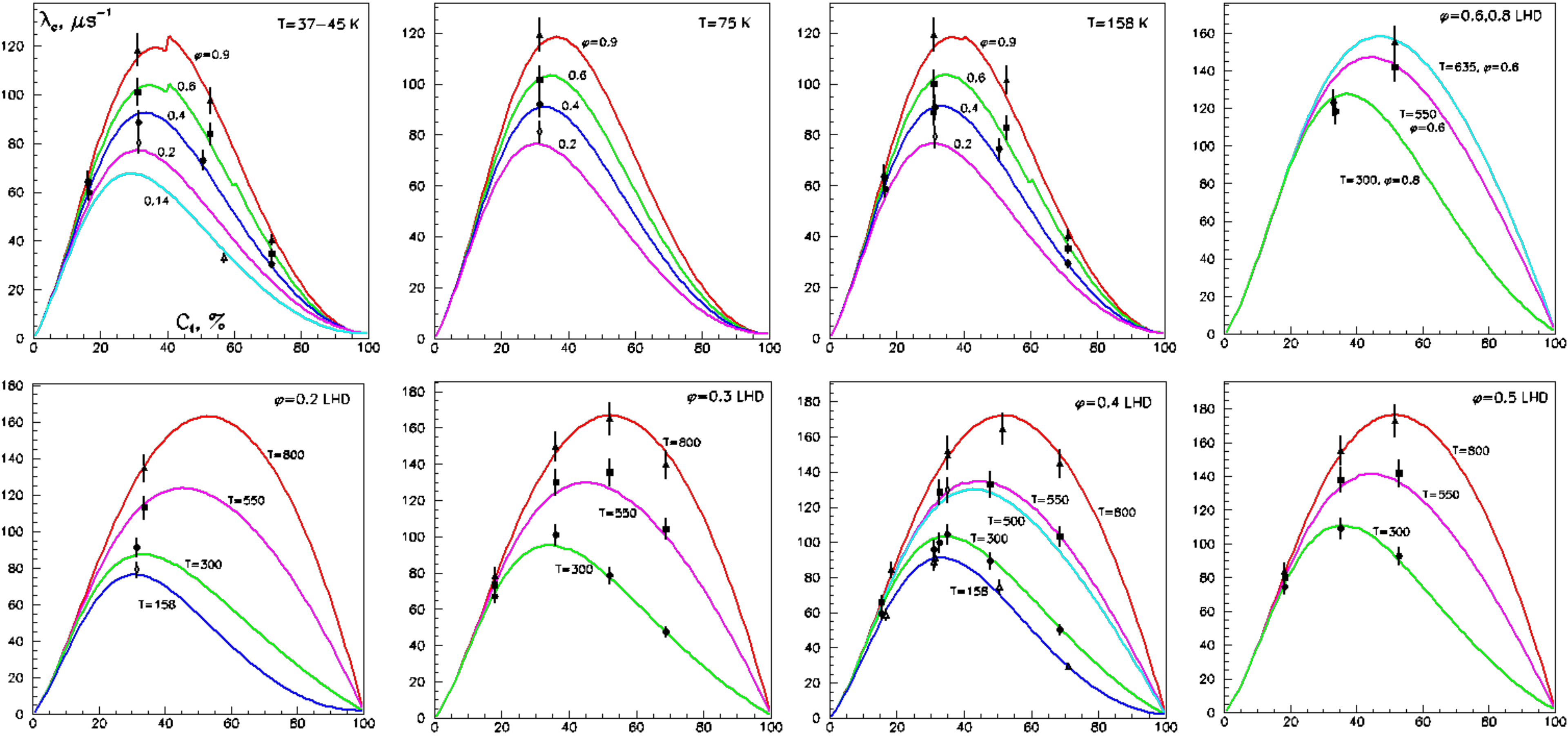
Normalized cycling rates (left) and muon loss probability (right) as a function of the tritium concentration for the liquid D/T mixture (22 K, 1.22 LHD).

Solid lines are optimum common fit. The dashed line is the value ωs

$\lambda dt\mu\text{-}d$ = (685 ± 35(stat) ± 41(syst)) μs^{-1}

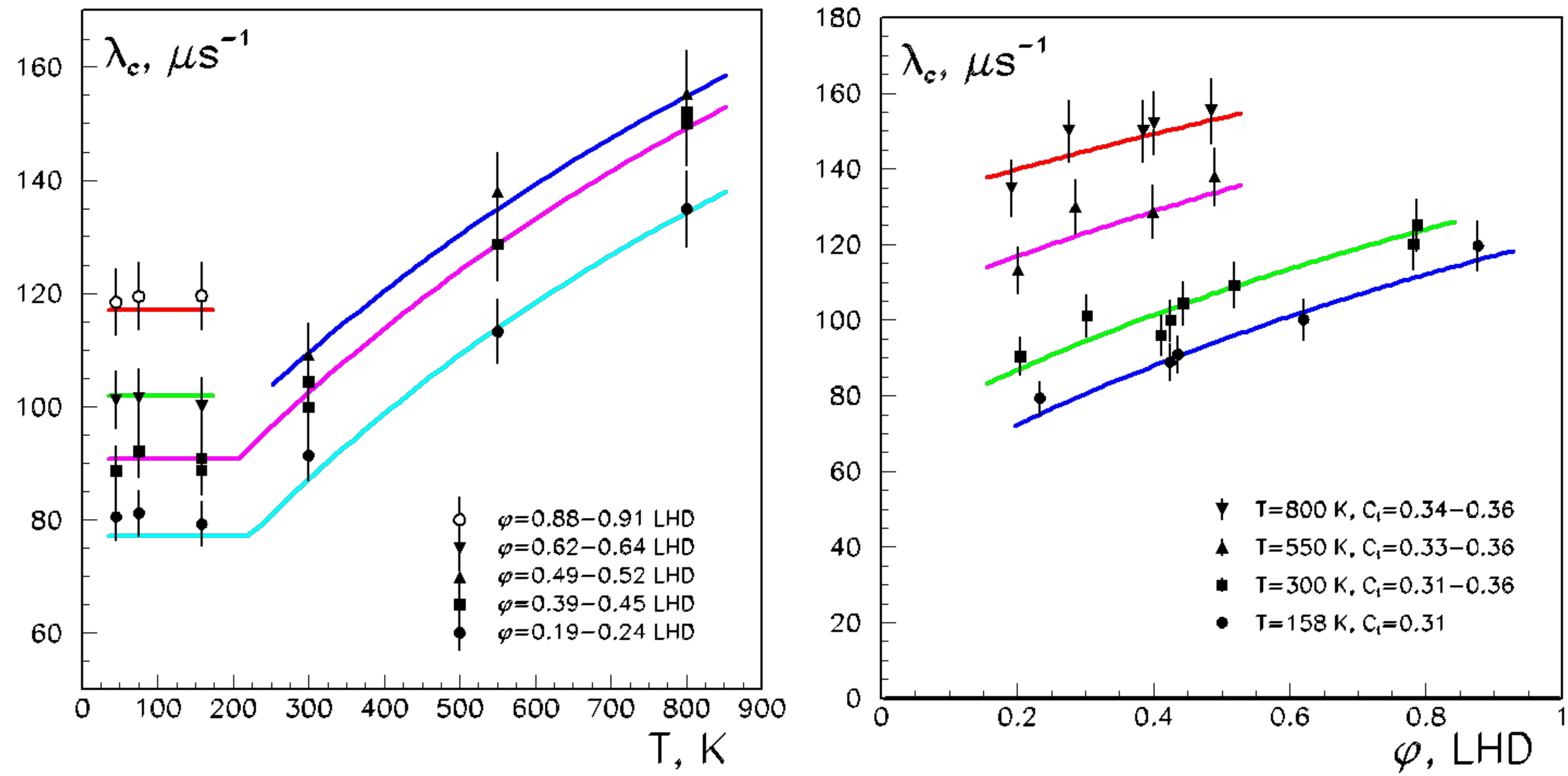
ωs = (0.573 ± 0.021(stat) ± 0.032(syst)) %

ω_s, %	Ref.	Comment
0.58	Cohen, 1988	theory for 1.2 LHD
0.58	Markushin, 1988	theory for 1.2 LHD
0.65	Kamimura, 1999	theory for 1.2 LHD
0.43 ± 0.05 ± 0.06	LAMPF, 1993	exp. for 1.2LHD slope
0.48 ± 0.02 ± 0.04	PSI, 1993	exp. for 1.2LHD slope
0.532 ± 0.030	RIKEN, 2001	exp. for 1.2LHD slope
0.505 ± 0.029	PSI, 2001	exp. for 1.45LHD combined slope and direct extrapolated to φ = 1.45 LHD
0.573 ±0.021± 0.032		this exp. for 1.22LHD slope and multiplisity

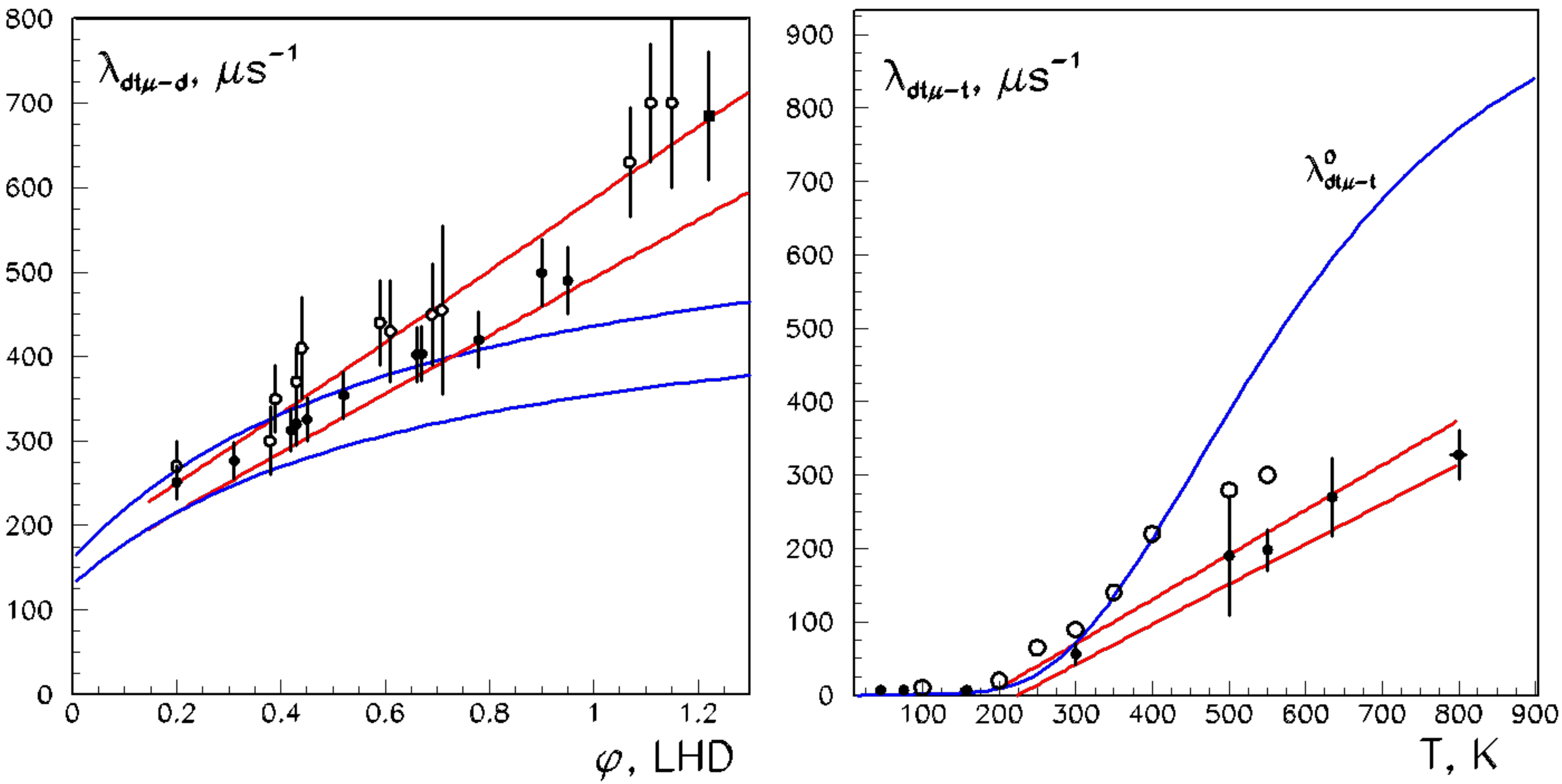


Common fit of the normalized cycling rates as a function of the tritium concentration for all (76 points) data for the gaseous D/T mixture (T=37-800 K, φ = 0.14-1.02 LHD). Lines are the optimum fit

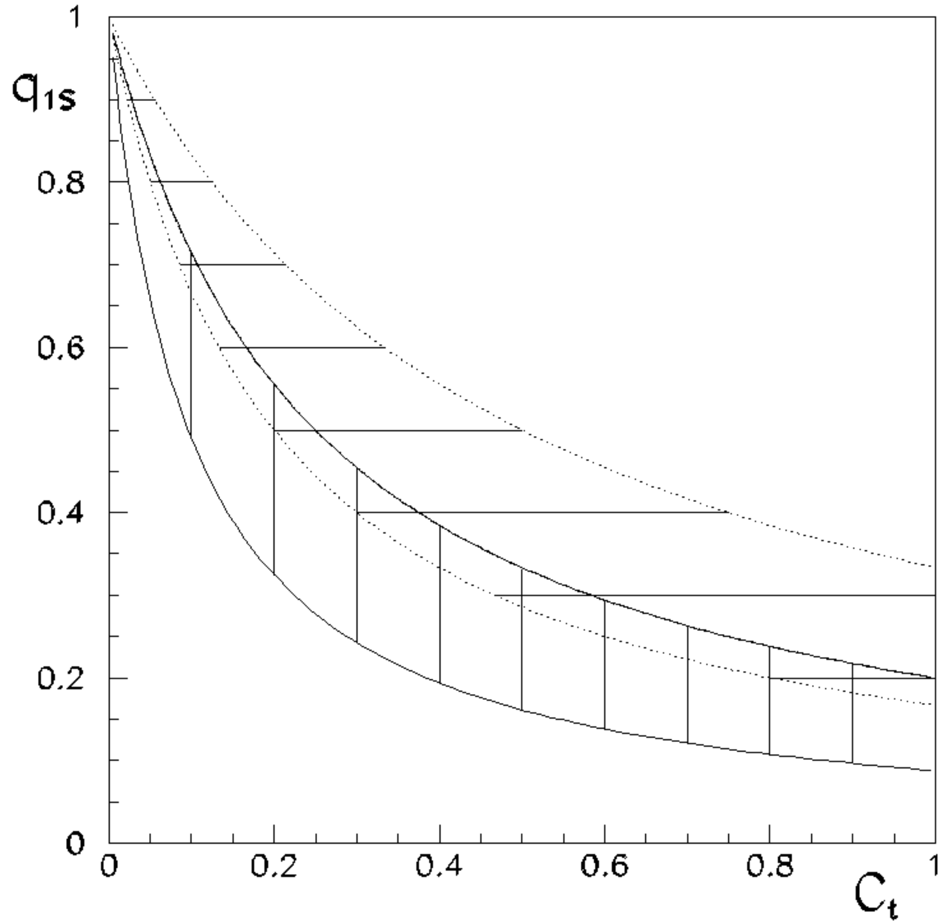
$$\frac{1}{\lambda_c} \approx \frac{q_{1S} C_d}{\lambda_{dt} C_t} + \frac{0.75}{\lambda_{1-0} C_t} + \frac{1}{\lambda_{dt\mu-d} C_{\mathrm{DD}} + \lambda_{dt\mu-t} C_{\mathrm{DT}}}$$



Left: normalized cycling rates as a function of temperature for gaseous D/T mixture at $C_t \approx 33\%$ and different densities.
Right: normalized cycling rates as a function of density for gaseous D/T mixture at $C_t \approx 33\%$ and different temperatures.
The curves are obtained with optimum parameters



Left: λdtμ - d as a function of density for T ≤ 300 K. Filled circles are JINR points for gas, empty circles are the results of LAMPF, the square is JINR result for liquid.
Red lines are the permissible values found from the fit.
Blue lines are limits for the λdtμ - d region obtained in PSI.
Right: λdtμ - t as a function of temperature. Filled circles are JINR points, empty circles are the results of LAMPF.
The blue line is the theory (Faifman). Red lines are limits of parameterization.



q_{1S} as a function of the tritium concentration.

The vertical shading is the parametrization obtained by current fit. The horizontal shading is the PSI result on the measurements at low temperature 40 K.

Discussion for D/T mixture

I. Muon sticking probability

The experimental values of ω_s obtained by different experimental groups are in satisfactory agreement with each other.
The value obtained by the direct method remarkably coincides with the one determined from the analysis of the muon losses as a function of the tritium concentration.
At the same time there remains some disagreement between experiment and theory.

II. q_{1S}

Analysis of the experimental data confirms the theoretical conclusion about the significant role of the muon transfer from the excited dμ-atom states.
According to the theory, the intensity of this process turns out to depend on the tritium concentration.
The probability q_{1S} of muon reaching the dμ-atomic 1S-state is successfully described by rather simple expression $q_{1S}=1/(1+a\cdot C_t)$ with the same parameter a for different C_t.
At the same time, contrary to the theoretical predictions, q_{1S} does not show noticeable density dependence.
These conclusions coincide with those made in the PSI analysis.

III. λdtμ

The most important results for D/T mixture:

$*$ at low temperatures (up to 300 K) the formation of the dtμ-molecules occur on D_2 molecules in three-body collisions of type

$$t\mu + D_2 + D_2 \rightarrow [(dt\mu)d,2e]^* + D_2'$$

and its rate linearly depends on the mixture density;

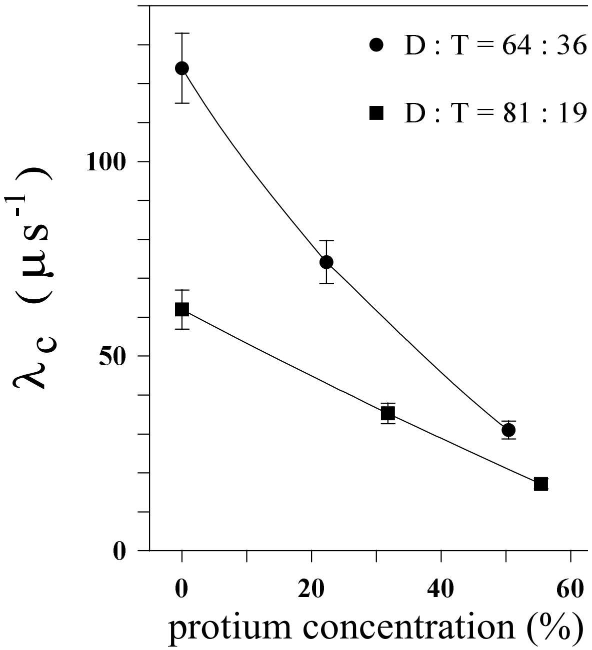
$*$ at highest temperatures the formation of dtμ occur on D_2 and DT molecules according to standard Vesman mechanism, however, the intensity of the process turns out to be lower than the calculated one.

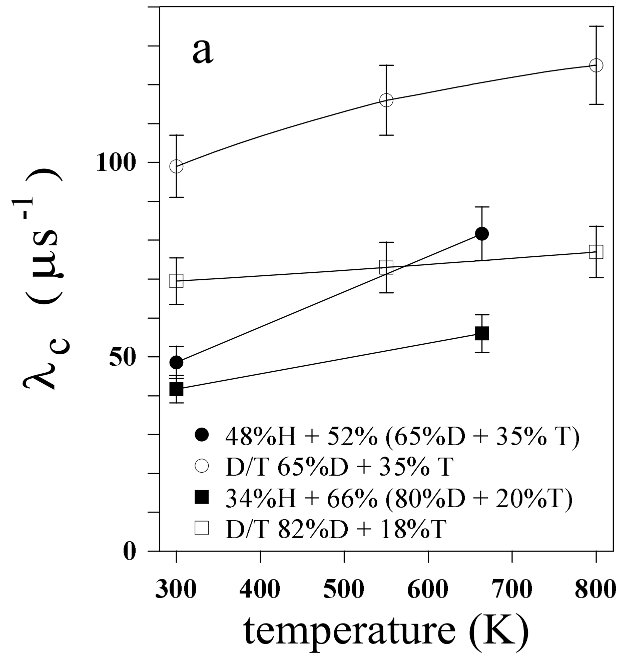
MCF experiments with H/D/T mixtures

According to the theory, the investigations of MCF in triple H/D/T mixture represents the special interest:

- $*$ most intensive resonance on HD;
- $*$ anamalous low $\sigma_{\mathbf{t\mu\ +p}}$ and $\sigma_{\mathbf{d\mu\ +p}}$;
- $*$ high λpt and λdt ($\varepsilon_{d\mu}$).

We were able to carry out the unique measurements with liquid and high pressure gaseous H/D/T mixtures.



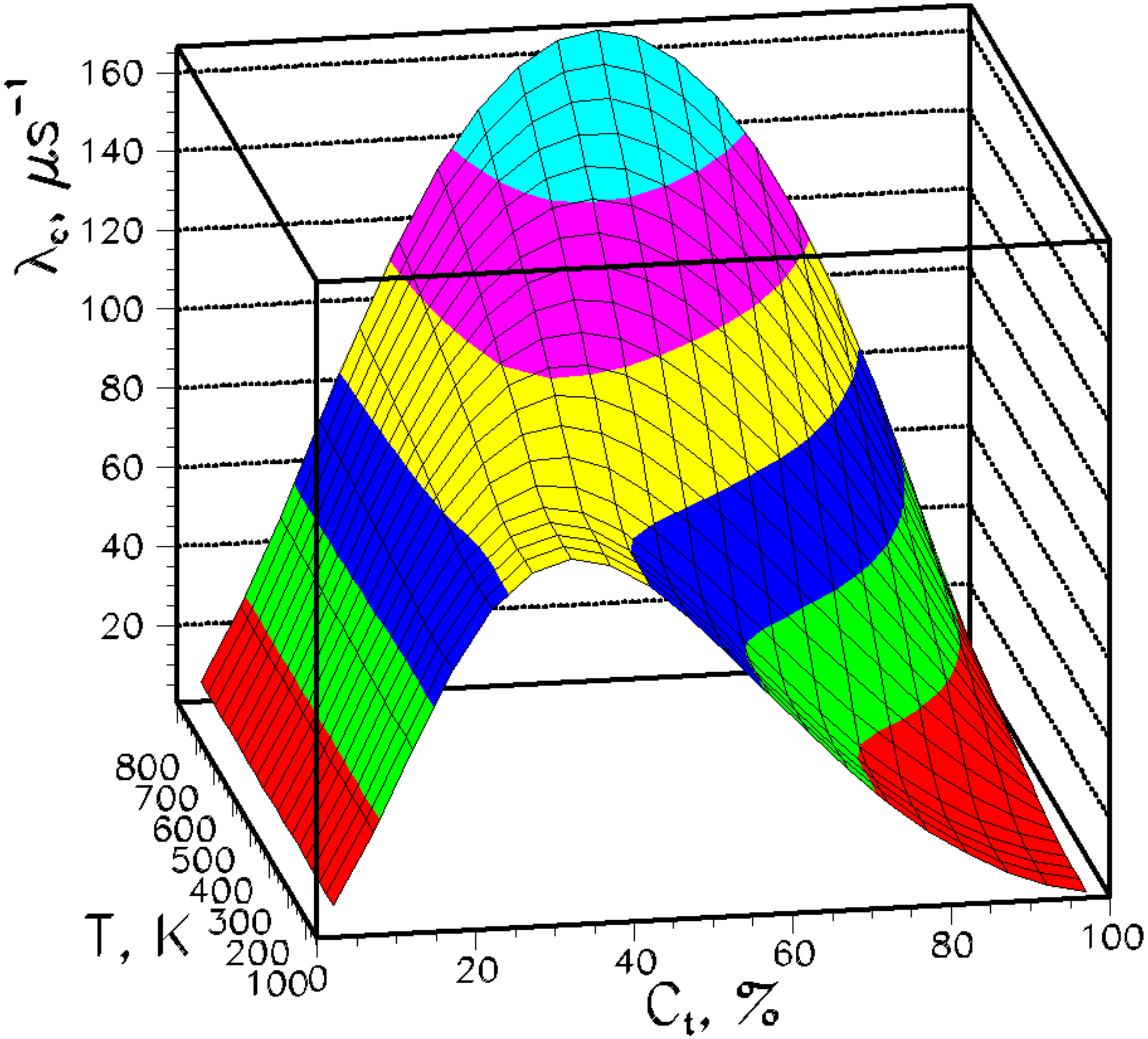


At low temperatures the change in thermalization rate is not so high to feel the HD resonance. Decrease of the d-t reaction yield with Ct is trivially explained by decrease of D_2 molecule fraction in the mixture.

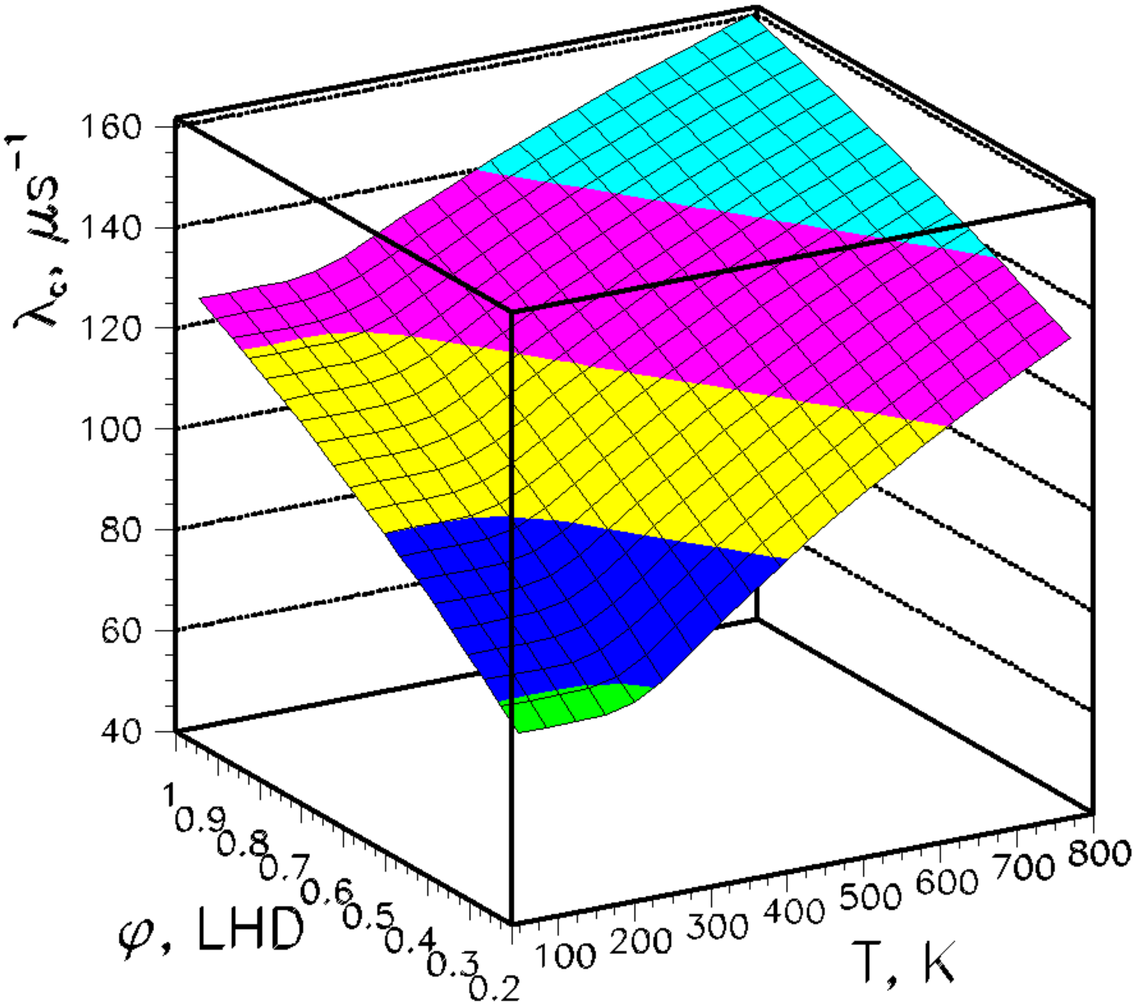
At high T, where the Maxwell ($\varepsilon_{t\mu}$) overlaps the resonances, protium addition provides the faster growth of λc with T as compare with DT mixture. It means that the resonance on HD is realized and its intensity is high.

Conclusion

The systematic experimental investigations of the MCF process in D/T and H/D/T mixture have been conducted at the JINR Phasotron by the novel method.
Measurements were made in a wide range of the mixture parameters – density, temperature and tritium concentration.



Normalized cycling rate as a function of tritium concentration and temperature for φ = 0.4 LHD plotted with the use of optimum parameterizations obtained from fit.



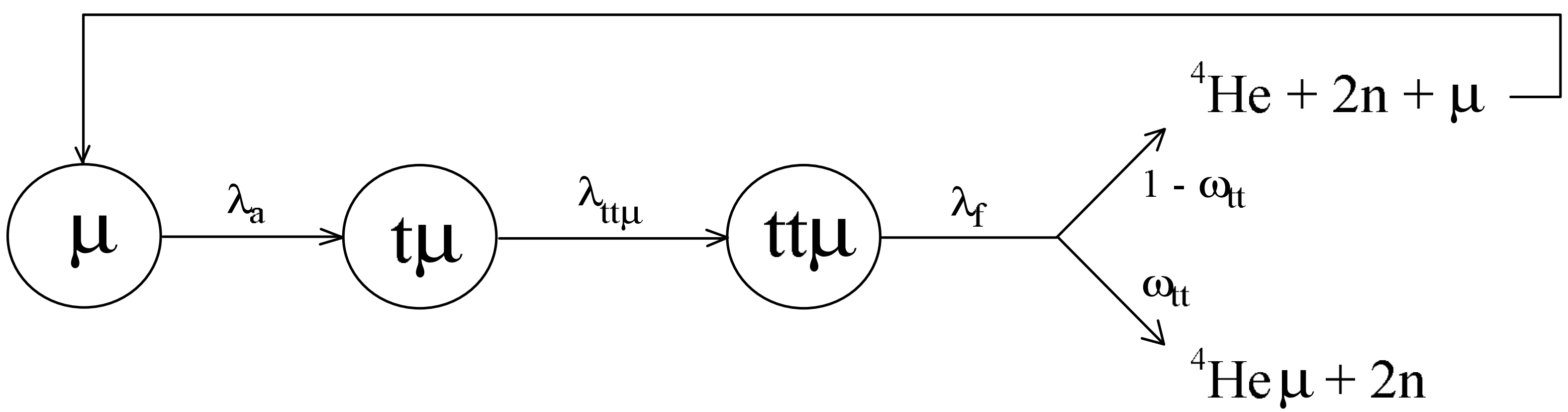
Normalized cycling rate as a function of temperature and density for C_t = 35% plotted with the use of optimum parameterizations obtained from fit.

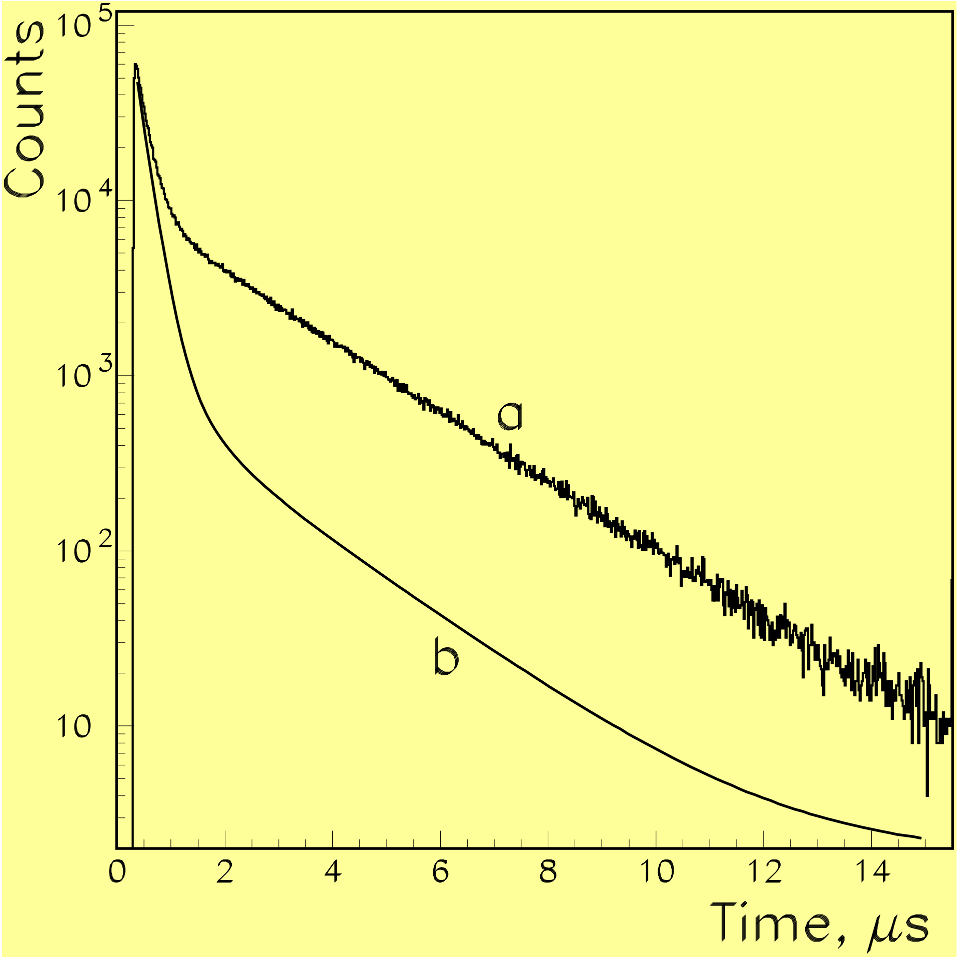
Analysis of the data allows us to determine the basic MCF parameters. In general they are in agreement with the ones obtained by other groups in the region where the experimental conditions were similar. The comparison of the experimental data with the theory confirms the efficiency of the main mechanisms considered in the MCF theory but the full qualitative description of the process is not achieved yet.

In our opinion, it will be very important to make measurements with a D/T mixture at the highest temperatures T=(1000-2000)K where the main resonances manifest themselves most effectively.

Experimental investigation of muon catalyzed t+t fusion

$t + t \rightarrow {}^4He + n + n + 11.3\ MeV$

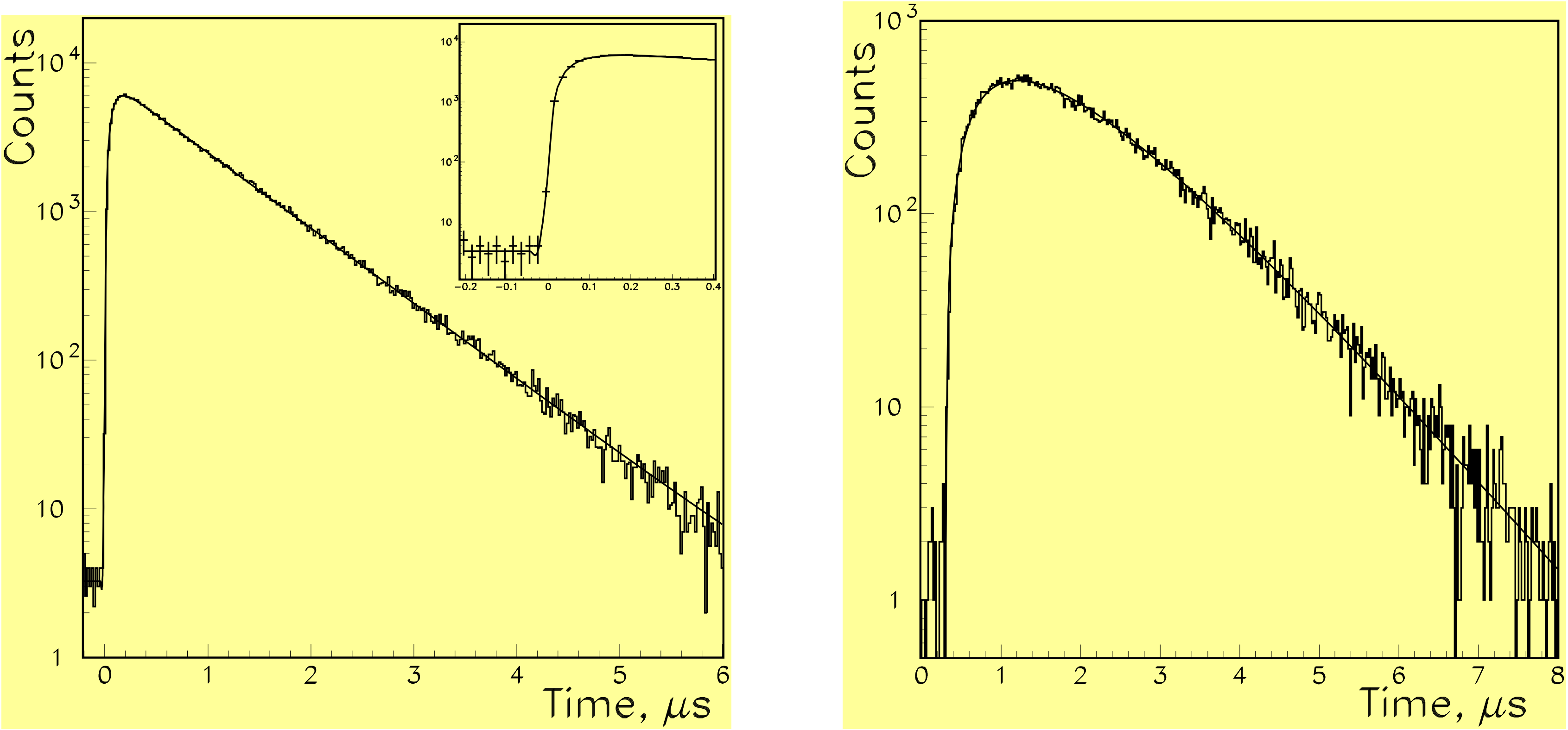




Electron (from muon decay) time distribution:

a – with tritium filled target; b – with empty target. Lines are fits.

In all we accumulated about 970,000 muons stopped in tritium.



Time distributions of the first (left) and second (write) measured neutrons from t+t reaction.

Solid lines are optimum fits.

Results of the measurements on the MCF cycle parameters:

$$\boldsymbol{\omega_{tt} = (13.9 \pm 1.5)\ \%}$$

$$\boldsymbol{\lambda_{tt\mu} = (2.84 \pm 0.32)\ \mu s^{-1} \qquad \lambda_f = (15.6 \pm 2.0)\ \mu s^{-1}}$$

PSI experiment:

ωtt = (14 ± 3) % λttμ = (1.8 ± 0.6) μs-1 λf = (15 ± 2) μs-1

RIKEN-RAL experiment:

ωtt = (8.7 ± 1.9) % λttμ = (2.4 ± 0.6) μs-1

Theory:

ωtt = 14 % λttμ = (2.96 or 2.64) μs-1 λf = 13 μs-1