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Method of determination of muon catalyzed fusion parameters in H-T mixture

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Abstract. A method for measurement of the muon catalyzed fusion parameters μCF in the H-T mixture is proposed. The kinetics of the mu-atomic and mu-molecular processes preceding the pt reaction in the $pt\mu$ molecule is described. Analytical expressions are obtained for the yields and time distributions of γ quanta and conversion muons formed in nuclear fusion reactions in $pt\mu$ molecules. It is shown that information on the desired parameters can be found from the joint analysis of the time distributions of γ quanta and conversion muons to be obtained in experiments with the H-T mixture at three (and more) appreciable different atomic concentrations of tritium. The experiments with the H-T mixture at the meson facility PSI (Switzerland) are planned to be optimized to gain the precise information about the desired μCF parameters.

PACS. 25.10.+s Nuclear reactions involving few-nucleon systems – 25.60.Pj Fusion reactions – 36.10.-k Exotic atoms and molecules (containing mesons, muons, and other unusual particles)

1 Introduction

The pt-reaction is one of the least known of all processes of muon catalyzed fusion (μCF) in the mixture of hydrogen isotopes. It is very important to gain information on reaction characteristics of all muonic processes in the H-T mixture (*e.g.*, the rate of muon transfer from $p\mu$ atom to triton, the rate of transition between hyperfine levels of $t\mu$ atoms, the rate of formation of the $pt\mu$ molecule, and the rate of nuclear synthesis in it) to interpret correctly the results of experiments in the triple mixture of hydrogen isotopes H-D-T and to describe the kinetics of all processes occurring in the mixture. From the theoretical point of view, the experiments investigating μCF processes in hydrogen-tritium mixture will allow one to test an algorithm describing a three-body system of particles interacting according to Coulomb rule.

It is necessary to emphasize the importance of the μCF study in H-T mixture in order to obtain the information about characteristics of pt-reaction at ultra low energy range (~keV)[1].

The investigation of the reaction between light nuclei at ultra-low energies (~keV) is very important for verification of fundamental symmetries in strong interactions [1–3], the contribution of meson exchange currents [4–7] and to solve some astrophysical problems [8–10].

With classical accelerators, it is practically impossible to study the pt-reaction in direct collision at very low energies (~keV) because the cross-sections of it and intensities of proton (triton) beams are very small [11–14].

At present, there are only two experiments [15,16] that investigate characteristics of μCF in an H-T mixture[2]. Only one [15] was performed with a H-T mixture and the second [16] with triple mixture H-D-T (no doubt, exact measurements of the parameters of muon catalyzed fusion of the pt reaction can be achieved only with the double mixture H-T).

In this paper we give the detail description of the kinetics of μCF for what is essential for data analysis of experimental results with the H-T mixture. Add the aim of this paper is to choose optimal conditions of the experiment for precision investigation of muonic processes in the H-T mixture.

2 Kinetics

The scheme of μ-atomic and μ-molecular processes in the H-T mixture after the negative muons stopped, is shown in

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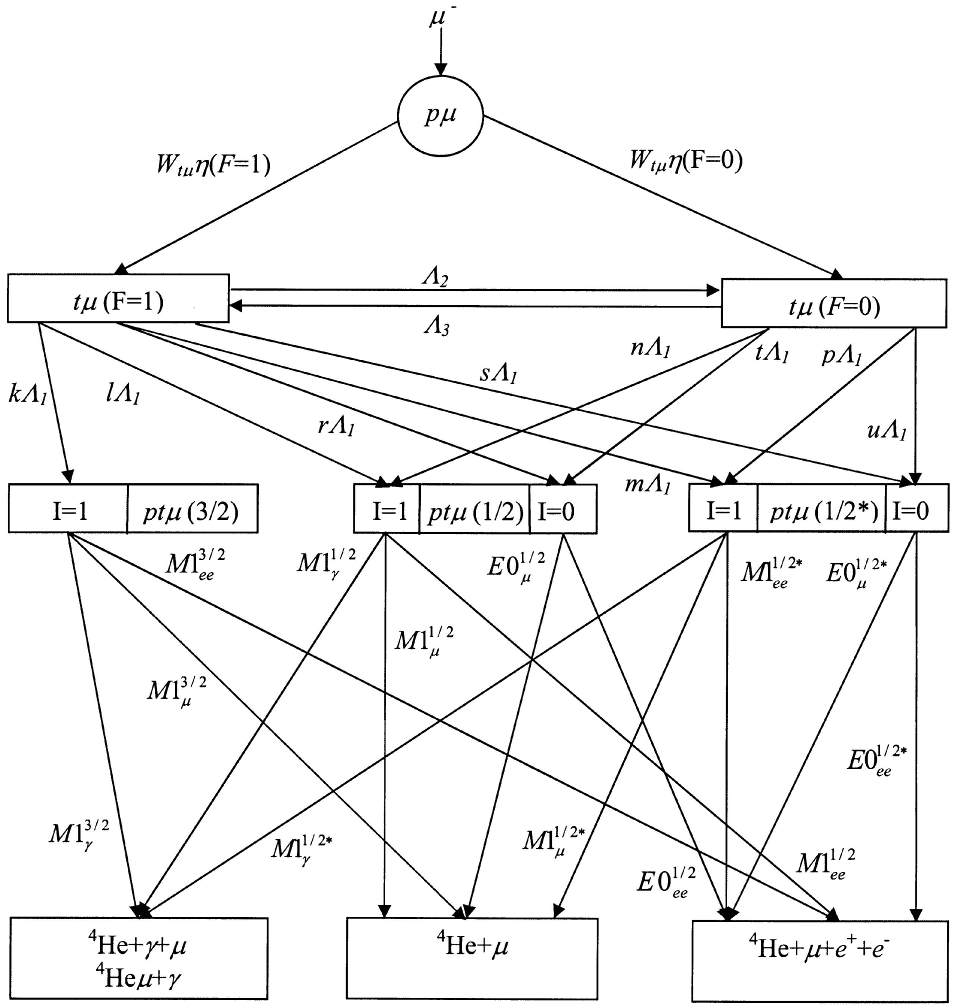
[1] In nuclear fusion reactions in the muonic molecules of hydrogen isotopes the astrophysical range of energies (~keV) is realized [11–14].

[2] Recently, on the TRIUMF meson facility the investigation of the processes of muonic atom ($p\mu$, $d\mu$, $t\mu$) interaction with hydrogen lattice at temperature of 3 K have been performed. The preliminary results of $pt\mu$ molecule formation rate have obtained [17,18].



$M1_{\gamma}^{3/2} = W_{3/2}^{1}\lambda_{f,\gamma}^{pt}(I=1)$, $M1_{\mu}^{3/2} = W_{3/2}^{1}\lambda_{f,\mu}^{pt}(I=1)$, $M1_{ee}^{3/2} = W_{3/2}^{1}\lambda_{f,ee}^{pt}(I=1)$;

$M1_{\gamma}^{1/2} = W_{1/2}^{1}\lambda_{f,\gamma}^{pt}(I=1)$, $M1_{\mu}^{1/2} = W_{1/2}^{1}\lambda_{f,\mu}^{pt}(I=1)$, $M1_{ee}^{1/2} = W_{1/2}^{1}\lambda_{f,ee}^{pt}(I=1)$,

$E0_{\mu}^{1/2} = W_{1/2}^{0}\lambda_{f,\mu}^{pt}(I=0)$, $E0_{ee}^{1/2} = W_{1/2}^{0}\lambda_{f,ee}^{pt}(I=0)$;

$M1_{\gamma}^{1/2*} = W_{1/2*}^{1}\lambda_{f,\gamma}^{pt}(I=1)$, $M1_{\mu}^{1/2*} = W_{1/2*}^{1}\lambda_{f,\mu}^{pt}(I=1)$, $M1_{ee}^{1/2*} = W_{1/2*}^{1}\lambda_{f,ee}^{pt}(I=1)$,

$E0_{\mu}^{1/2*} = W_{1/2*}^{0}\lambda_{f,\mu}^{pt}(I=0)$, $E0_{ee}^{1/2*} = W_{1/2*}^{0}\lambda_{f,ee}^{pt}(I=0)$;

$\Lambda_1 = \varphi C_p \lambda_{pt\mu}$, $\Lambda_2 = C_t \varphi \lambda_{10}$, $\Lambda_3 = C_t \varphi \lambda_{01}$.

Fig. 1. Kinetics of the muonic processes in H-T mixture.

Figure 1. As a result of the muon transfers from $p\mu$-atom to tritium nuclei

$$p\mu + t \rightarrow t\mu + p + 183 \text{ eV} \tag{1}$$

$t\mu$ atoms are formed with the kinetic energy of about 45 eV (the scheme in Fig. 1 corresponds to a very low tritium concentration in the H-T mixture ($\leq$1%), which allows one to neglect direct capture of the muon by tritium).

The ground state of the $t\mu$ atom is split into two hyperfine structure levels with $\mathbf{F} = \mathbf{S}_t + \mathbf{S}_\mu$ being the total spin of the $t\mu$ atom ($S_t = S_\mu = 1/2$ are the spins of triton and muon, respectively) equal to $F = 1$ $((\mathbf{S}_t\mathbf{S}_\mu) \equiv (\uparrow\uparrow))$ and $F = 0$ $((\mathbf{S}_t\mathbf{S}_\mu) \equiv (\uparrow\downarrow))$. The energy of hyperfine splitting of the $t\mu$ atom equals 0.24 eV. The initial population of hyperfine levels is assumed statistically to be:

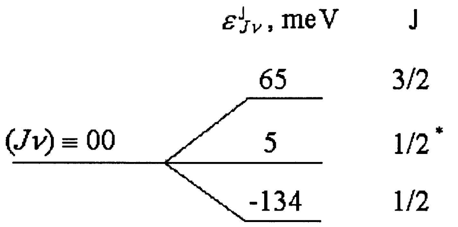
$$\eta = 3/4\ (F=1), \quad \eta = 1/4\ (F=0).$$

In the collision of $t\mu$ atoms with H_2 or HT molecules

$$t\mu + H_2 \rightarrow ((pt\mu)^+ pe)^+ + e^- \tag{2}$$

$$t\mu + \text{HT} \rightarrow ((pt\mu)^+ te)^+ + e^- \tag{3}$$

the $pt\mu$ molecule is formed by the electric dipole transition El in excited state (J, ν), (where J, ν are rotational and vibrational quantum numbers of the pt-system in $pt\mu$ molecule, respectively).



J	W_J^1	W_J^0
3/2	0	1
1/2*	0.967	0.033
1/2	0.033	0.967

Fig. 2. Scheme of the energy sublevels of $pt\mu$ molecule ground state [19]: W_J^0, W_J^1 are the probabilities that the sum of spins of proton and triton in the $pt\mu$ molecule, $(\mathbf{I} = \mathbf{I}_p + \mathbf{I}_t)$, in the state with angular momentum J equals 0 and 1.

At the collision of the $t\mu$ atom with triton in the T_2 or HT molecule, the formation of a $tt\mu$ molecule is possible

$$t\mu + T_2 \to ((t\mu t)^+ te) + e^- \quad (4)$$

$$t\mu + HT \to ((t\mu t)pe) + e^- \quad (5)$$

due to El dipole transition.

The competitive processes to the formation of a $pt\mu$ molecule are: free muonic decay ($\mu \to e^- + \nu_\mu + \tilde{\nu}_e$), $tt\mu$ molecule formation (processes (4) and (5)) and the $t\mu$ atom transition between hyperfine levels.

$$t\mu(F=1) + t \xrightarrow{\lambda_{10}} t(F=0) + t, \quad (6)$$

$$t\mu(F=0) + t \xrightarrow{\lambda_{01}} t\mu(F=1) + t. \quad (7)$$

The transition (7) is possible only when the energy of the $t\mu$ atom fulfills the condition: $E_{t\mu} > \Delta E = 0.24$ eV (ΔE is energy of hyperfine splitting of the ground state of the $t\mu$ atom). The probability of the transition of a $t\mu$ atom between hyperfine levels due to the collision of $t\mu$ atom with a proton

$$t\mu(F=1) + p \underset{\lambda_{01}}{\overset{\lambda_{10}}{\rightleftarrows}} t\mu(F=0) + p \quad (8)$$

according to [21,22] is very small (because of the small rate of spin-flip reactions due to spin-spin interactions compared to the rate of charge exchange reactions).

The transition of $pt\mu$ molecule from the state with $(J\nu) = (10)$ to the ground state $(J\nu) = (00)$ proceeds very quickly ($\sim 10^{-11}$ s) and the energy difference between two states is carried out by conversion electron.

The ground state of the $pt\mu$ molecule is split into three sublevels with total momentum $\mathsf{J} = I + S = 3/2$, $1/2$, $1/2^*$ [19,20] (see Fig. 2).

The binding energy of the ground state of the $pt\mu$ molecule (in the non relativistic case) equals $\varepsilon_{00} = 214$ keV.

As it is seen from Figure 2 and Table 1, the probability of the formation of a $pt\mu$ molecule in the state with total momentum J and nuclear spin $I = 1$ in the collision of $t\mu$ atom in the ortho-state with a proton is smaller than during the collision of $t\mu$ atom in the para-state (see Appendix A).

The populations of the states with different J, J, I and S (S is the total spin of $pt\mu$ molecule) depend on

Table 1. The population of $pt\mu$ molecule levels, formed in the collision of a $t\mu$ atom in the para ($F = 0$) or ortho-state ($F = 1$) [20] with a proton. $\varepsilon_{J,\nu}$ is the energy of the stationary state of the $pt\mu$ molecule $(J\nu)$ in the non relativistic case; $\varepsilon^{\mathsf{J}}_{J\nu}$ is the energy of the stationary state of the molecule $pt\mu$ $(J\nu)$ with total momentum J deduced from $\varepsilon_{J\nu}$; $a^{\mathsf{J}}_{J\nu}$ $(\uparrow\downarrow)$, $a^{\mathsf{J}}_{J\nu}$ $(\uparrow\uparrow)$ are the populations of the state (J, ν, J) of the $pt\mu$ molecule, created in the collision of a $t\mu$ atom in the para – ($F = 0$) or ortho – ($F = 1$) state, respectively, with a proton.

J	ν	$\varepsilon_{J\nu}$, eV	J	$\varepsilon^{\mathsf{J}}_{J\nu}$, eV	$a^{\mathsf{J}}_{J\nu}$ $(\uparrow\downarrow)$	$a^{\mathsf{J}}_{J\nu}$ $(\uparrow\uparrow)$
			1/2*	0.0046	0.1120	0.2960
0	0	−214.0	1/2	−0.1344	0.8880	0.0373
			3/2	0.0649	0	0.6667
				0.0053	0.0256	0.1026
			1/2	−0.1249	0.3076	0.0086
				0.0555	0.0001	0.1111
1	0	−99.0		0.0083	0.0548	0.2039
			3/2	−0.1262	0.6119	0.0183
				0.0608	0	0.2222
			5/2	0.0594	0	0.3333

the relations between the rate of the loss of the energy by the $t\mu$ atom (due to elastic and non-elastic collisions with H_2, HT and T_2 molecules), the rates of the processes (6–7) (λ_{10}, λ_{01}), and also on the relation between the above mentioned rates and the rate of the $pt\mu$ molecule formation.

The whole set of nuclear reactions occurring in the $pt\mu$ molecule in different states:

$$pt\mu \longrightarrow \left| \begin{array}{lll} \to {}^4\mathrm{He} + \mu + \gamma & (19.76\ \mathrm{MeV}) & (9a) \\ \to {}^4\mathrm{He}\,\mu(1s) + \gamma & (19.77\ \mathrm{MeV}) & (9b) \\ \to {}^4\mathrm{He}\,\mu(2p) + \gamma & & (9c) \\ \to {}^4\mathrm{He}\,\mu(n>2) + \gamma & & (9d) \\ \to {}^4\mathrm{He} + \mu & (19.22\ \mathrm{MeV}) & (9e) \\ \to {}^4\mathrm{He}\,\mu + e^+ + e^- & & (9f) \\ \to {}^4\mathrm{He}\,\mu + \gamma + \gamma & & (9g) \end{array} \right.$$

The production of 19.8 MeV γ quanta (M1-transition) is possible only from the state of $pt\mu$-molecule with the total nuclear spin $I = 1$ (reactions (9a–9d)).

Non radioactive transitions (9e) and (9f) proceed dominantly *via* the monopol EO transition. The probability for the reaction channel (9g) is negligibly small.

The values of the partial rates for the different $pt\mu$ decay channels can be written as:

$$\lambda_{f,i}^{pt}(\mathsf{J}) = \rho(W_{\mathsf{J}}^{0}K_{0}^{i} + W_{\mathsf{J}}^{1}K_{1}^{i}) \quad (10)$$

where $i \equiv \gamma$, μ, e^{+}, e^{-}, 2γ; ρ is the density of the probability that the distance between the proton and triton in the $pt\mu$ molecule equals 0 and K_{0}^{i}, K_{1}^{i} are pt reaction constants for S wave in the nuclear states with $I = 0$ (singlet) and $I = 1$ (triplet).

For the theoretical description of the pt reaction we use the resonant model of the existence of ^{4}He nuclei in excited state 0^{+} near the threshold of this reaction. It is seen from Figure 1 that transitions (6–7) change the populations of the state of the $pt\mu$ molecule (the population of the state with $\mathsf{J} = 3/2$ decreases, therefore together with the $pt\mu$, molecule formation, the process of thermalization of $t\mu$ atoms proceeds) which can change not only the yield of the reaction products (9) but also the ratio between the partial probabilities for different channels of the reaction.

Below, the kinetics of the $pt\mu$ cycle is presented under the assumption that the rates of all muonic processes in the H-T mixture do not depend on energy and that thermalization of $t\mu$ atoms occurs sufficiently fast. The expected average time of thermalization of $t\mu$ atoms $t_{\rm term} \approx 10-30$ ns (depending on density of the target) is considerably smaller than characteristic times of all other muonic processes in the H-T mixture.

The yields and time distributions of γ quanta with energy 19.8 MeV and the conversion muons with energy 19.2 MeV, formed in the pt reaction, can be described by the following expressions:

$$\frac{\mathrm{d}N_{\gamma}}{\mathrm{d}t} = A_{1}^{\gamma}\mathrm{e}^{-\lambda_{1}t} + A_{2}^{\gamma}\mathrm{e}^{\lambda_{2}t} + A_{3}^{\gamma}\mathrm{e}^{-\lambda_{3}t} + A_{4}^{\gamma}\mathrm{e}^{-\lambda_{4}t}, \quad (11)$$

$$\frac{\mathrm{d}N_{\mu}}{\mathrm{d}t} = A_{1}^{\mu}\mathrm{e}^{-\lambda_{1}t} + A_{2}^{\mu}\mathrm{e}^{-\lambda_{2}t} + A_{3}^{\mu}\mathrm{e}^{-\lambda_{3}t} + A_{4}^{\mu}\mathrm{e}^{-\lambda_{4}t} + A_{5}^{\mu}\mathrm{e}^{-\lambda_{5}t}, \quad (12)$$

$$N_{\gamma} = \frac{A_{1}^{\gamma}}{\lambda_{1}} + \frac{A_{2}^{\gamma}}{\lambda_{2}} + \frac{A_{3}^{\gamma}}{\lambda_{3}} + \frac{A_{4}^{\gamma}}{\lambda_{4}}, \quad (13)$$

$$N_{\mu} = \frac{A_{1}^{\mu}}{\lambda_{1}} + \frac{A_{2}^{\mu}}{\lambda_{2}} + \frac{A_{3}^{\mu}}{\lambda_{3}} + \frac{A_{4}^{\mu}}{\lambda_{4}} + \frac{A_{5}^{\mu}}{\lambda_{5}}, \quad (14)$$

$$\lambda_{1} = \lambda_{0} + \lambda_{pp\mu}\varphi C_{p} + \lambda_{pt}\varphi C_{t}, \quad (15)$$

$$\lambda_{2} = \lambda_{0} + \lambda_{pt\mu}\varphi C_{p} + \lambda_{tt\mu}\varphi C_{t} + \lambda_{10}\varphi C_{t}, \quad (16)$$

$$\lambda_{3} = \lambda_{0} + \lambda_{pt\mu}\varphi C_{p} + \lambda_{tt\mu}\varphi C_{t}, \quad (17)$$

$$\lambda_{4} = \lambda_{0} + \lambda_{f}^{pt}(I = 1), \quad (18)$$

$$\lambda_{5} = \lambda_{0} + \lambda_{f}^{pt}(I = 0), \quad (19)$$

$$\gamma_{0} = 0.455 \times 10^{6}\ \mathrm{s}^{-1} \qquad C_{p} + C_{t} = 1$$

where $A_{1}^{\gamma} \div A_{4}^{\gamma}$, $A_{1}^{\mu} \div A_{5}^{\mu}$ are the normalized coefficiences given in the Appendix B; N_{γ}, N_{μ} are the yields of γ quanta and conversion muons, respectively; $\lambda_{0} = 0.455\times10^{6}$ s^{-1} is the free muon decay rate; λ_{pt}, λ_{10}, $\lambda_{pt\mu}$ are the rates of the muon transition from $p\mu$ atom to triton, of the transition of $t\mu$ atom from the state with $F = 1$ to the state with $F = 0$, and of the $pt\mu$ molecule formation, respectively (the above values are reduced to liquid hydrogen density, $n_{0} = 4.25 \times 10^{22}$ cm^{-3}); $\lambda_{f,\mu}^{pt}(I = 0)$, $\lambda_{f,\mu}^{pt}(I = 1)$ are partial rates of nuclear synthesis in the $pt\mu$ molecule with muon production for the total spin of proton and triton equal to 0 and 1, respectively, and $\lambda_{f,\mu}^{pt}(I = 1)$ is the rate of nuclear synthesis in the $pt\mu$ molecule in the state $I = 1$ with γ quanta production; $\lambda_{f}^{pt}(I = 0)$, $\lambda_{f}^{pt}(I = 1)$ are the rates of nuclear synthesis in the $pt\mu$ molecule for the total spin of proton and triton equal to 0 and 1, respectively; $\lambda_{f,ee}^{pt}(I = 0)$, $\lambda_{f,ee}^{pt}(I = 1)$ are the rates of nuclear synthesis in the $pt\mu$ molecule with the formation of an electron-positron pair for the total spin of p and t equal to 0 and 1, respectively; C_{p} and C_{t} are atomic concentrations of protium and tritium in H-T mixture; φ is the density of the H-T mixture reduced to liquid hydrogen density.

The measurement of the synthesis rate in the $pt\mu$ molecule with the production of conversion muons, $\lambda_{f,\mu}^{pt}(I = 0)$ is very important and will allow one to verify the validity of the hypothesis of the existence of a threshold resonance in the fusion channel (and to check the charge distribution in the system with $A = 4$).

Having time distributions of γ quanta with energy 19.8 MeV (reactions (9a–9d)) and conversion muons with energy 19.2 MeV (reaction (9e)) or electron-positron pair (reaction (9f)) for different tritium concentration C_{t}, using equations (11–14), one can derive unknown parameters: λ_{pt}, λ_{10}, $\lambda_{pt\mu}$, $\lambda_{f,\gamma}^{pt}(I = 1)$ and $\lambda_{f,\mu}^{pt}(I = 0)$. We assume the values of parameters $\lambda_{pp\mu}$, $\lambda_{tt\mu}$, k, l, m, n, p, r, s, t and u are known (the value $\lambda_{pp\mu}$ was taken as an average from papers [18,23–27], $\lambda_{tt\mu}$ from [28] and the remaining parameters were taken from [19,20].

This approach is valid, because the yields and time distributions of the products from different channels of the pt reaction require the same μCF parameters, which, on the one hand can guarantee correct interpretation of the results and correct estimation of systematic errors, and on the other hand can increase the accuracy of measured parameters.

3 Optimization and results description

The existing theoretical and experimental parameters describing the $pt\mu$-cycle are presented in Table 2.

As shown, there is big difference between experimental and theoretical values of some parameters like λ_{pt}, $\lambda_{f}^{pt}(I = 1)$, and $\lambda_{f}^{pt}(I = 0)$. Regarding the rate of the $pt\mu$ molecule formation ($\lambda_{pt\mu}$) there is strong disagreement between theory and experiment.

It is shown from Table 2 that it is necessary to measure fundamental characteristics of μCF in the H-T mixture to explain the nature of the difference between theoretical and experimental values. Figure 3 shows the dependence

Table 2. The experimental and theoretical values of the parameters of the μCF process in the H-T mixture.

	Experiment				Theory	
Value	H/T [15]	H/D/T [16]	H/T [17]	H/T [18]	[14]	[19]
λ_{pt}, 10^9 s^{-1}		9.3 ± 1.5	$5.86 \pm (0.10)_{\rm stat}$	5.8 ± 0.4		
λ_{10}, 10^9 s^{-1}	6.0 ± 0.5	1.0 ± 0.2				
$\lambda_{pt\mu}$, 10^6 s^{-1}		7.5 ± 1.3			0.4	
$\lambda_f^{pt}(I = 1)$, 10^4 s^{-1}	6.5 ± 0.7	7.0 ± 1.2			≈1800	7
$\lambda_f^{pt}(I = 0)$, 10^2 s^{-1}		$(15 \pm 4) \times 10^2$				8.6
$\lambda_{f,\gamma}^{pt}(I = 1)$, 10^6 s^{-1}						0.07
$\lambda_{f,ee}^{pt}(I = 1)$, 10^2 s^{-1}						2.4
$\lambda_{f,ee}^{pt}(I = 0)$, 10^2 s^{-1}						3.6
$\lambda_{f,\mu}^{pt}(I = 1)$ s^{-1}						0.35
$\lambda_{f,\mu}^{pt}(I = 0)$, 10^2 s^{-1}					10^3–10^4	5 ± 1
$\dfrac{\lambda_{f,\mu}^{pt}(I=1)}{\lambda_f^{pt}(I=1)}$					10^{-5}	5×10^{-6}
$\dfrac{\lambda_{f,\mu}^{pt}(I=0)}{\lambda_{f,ee}^{pt}(I=0)}$					≈1	0.73

There also exists some other, single theoretical estimates of the above parameters not shown in the table:
$\lambda_{pt} = 7.5 \times 10^9$ s^{-1} [22], (7.0–8.0) $\times 10^9$ s^{-1} at $T = 300-30$ K [29], 5.8×10^9 s^{-1} [30], 5.5×10^9 s^{-1} [31], 5.7×10^9 s^{-1} [32];
$\lambda_{10} = 0.89 \times 10^9$ s^{-1} [22], 0.91×10^9 s^{-1} [33], 1.3×10^9 s^{-1} [34];
$\lambda_{pt\mu} = 6.5 \times 10^6$ s^{-1} [35], 6.38×10^6 s^{-1} [36];
$\lambda_f^{pt}(I = 1) = 0.5 \times 10^6$ s^{-1} [37][a], 0.13×10^6 s^{-1} [38][b], 0.008×10^6 s^{-1} [40][b].

[a]These values were obtained according to the formula: $\lambda_f^{pt}(I = 1) = (4/3)K_0\rho_0$ using pt reaction constants K_0 from papers [37, 39], respectively and ρ_0 from [38]. [b]The estimate of this value was obtained [16] using the cross-section $\sigma(n, \gamma) = 55 \pm 3\,\mu b$ of the mirror reaction ^{3}He$(n, \gamma)^4$He [41,42].

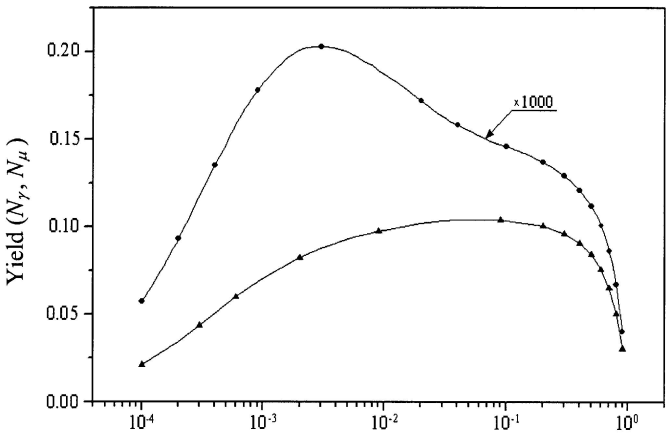


Fig. 3. The dependences of γ quantum (triangles) and conversion muon (circles) yields from pt fusion as a function of tritium concentration.

of the yield of γ quanta and conversion muons per one muon stopped in H-T mixture as a function of the tritium concentration C_t (calculated according to formulaes (13) and (14)) for a density of the H-T mixture equal to the density of liquid hydrogen, $\varphi = 1$. Comparing obtained dependences with corresponding values from paper [16] one can notice differences not only in shape but also in absolute values of conversion muon yield for the same values of C_t. The reason for such discrepancies is not clear.

According to [16] the maximum values of the γ quantum and conversion muon yields of calculated for one muon stopped in the H-T mixture equals $N_\gamma^{\max} \approx 0.11$ ($C_t \approx 6 \times 10^{-2}$) and $N_\mu^{\max} = 0.015$ (for $C_t = 3 \times 10^{-3}$), and in present paper $N_\gamma^{\max} \approx 0.10$ ($C_t \approx 8 \times 10^{-2}$), $N_\mu^{\max} \approx 2.0 \times 10^{-4}$ ($C_t \approx 3 \times 10^{-3}$).

The dependence of the ratio of the conversion muon and γ quanta yields as a function of tritium concentration is shown in Figure 4. The distinguishing feature of this dependence is that the ratio N_μ/N_γ is practically constant for a tritium concentration larger than 0.2. A such behavior of the N_μ/N_γ ratio can be explained by the existence of the Gershtein–Wolfenshtein effect predicted [43] and verified before for muon catalyzed fusion in H-D mixture [24]. There are six unknown parameters ε_γ, ε_μ, $\lambda_{f,\mu}^{pt}(I = 0)$, λ_{10}, $\lambda_{pt\mu}$, λ_{pt} in expressions (11–14) and to determine them with sufficient accuracy, three exposures of muon beam in the H-T mixture for three tritium concentrations are required. Really there are seven unknown parameters

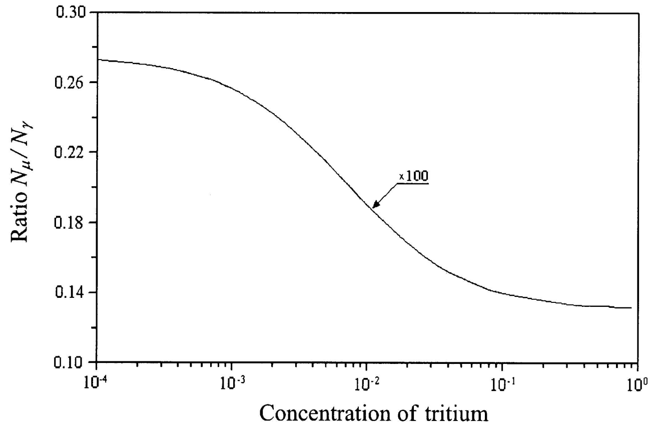


Fig. 4. Ratio between yields of conversion muon (N_μ) and γ quanta (N_γ) as a function of tritium concentration.

but the quantity $\lambda_f^{pt}(I=1)$ is determined from the slope of exponent with index λ_4: $\lambda_f^{pt}(I=1) = \lambda_4 - \lambda_0$ (see expression (18)).

According to [19] the partial rates of nuclear M1 transition in $pt\mu$ molecule with emission of conversion muon ($\lambda_{f,\mu}^{pt}(I=1)$) and electron–positron pair ($\lambda_{f,ee}^{pt}(I=1)$) are negligible in comparison with $\lambda_{f,\gamma}^{pt}(I=1)$. Therefore the following ratio is valid:

$$\lambda_{f,\gamma}^{pt}(I=1) \approx \lambda_f^{pt}(I=1) = \lambda_{f,\gamma}^{pt}(I=1) + \lambda_{f,\mu}^{pt}(I=1) + \lambda_{f,ee}^{pt}(I=1).$$

The accuracy of estimating these parameters depends on the statistic of detected events in the experiment. In principle, the rates of the processes $\lambda_{f,\gamma}^{pt}(I=1)$, λ_{10}, $\lambda_{pt\mu}$, λ_{pt} can be estimated from the slopes of exponents with indexes λ_1, λ_2, λ_3, λ_4 (expressions (15–18)). The value $\lambda_{f,\mu}^{pt}(I=0)$ can not be experimentally found from the slope of exponent with index λ_5 ($\lambda_5 = \lambda_{f,\mu}^{pt}(I=0) + \lambda_0$) because the value $\lambda_{f,\mu}^{pt}(I=0)$ is very small ($\lambda_f^{pt}(I=0) = 5\times10^2$ s^{-1} [19]) compared to λ_0 ($\lambda_5 \approx \lambda_0$). Therefore, the value $\lambda_{f,\mu}^{pt}(I=0)$ can only be found analyzing the factor A_5^μ before the exponent with index $\lambda_5 \approx \lambda_0$ in expression (19).

Below as an example of H-T experiment optimization it will considered the performance of experiment using the muon channel μE4 of PSI meson facility (Switzerland). As a target it is supposed to use the liquid hydrogen with tritium concentration C_t less than 10%. This value of tritium concentration is dictated by safety conditions.

The optimization of the planned experiment requires finding three tritium concentrations and corresponding times of the exposures, on the muon channel so that the errors of the determination of unknown parameters will be minimal (this means that the sum of the squares of the relative errors of the desired parameters is minimal in the interval $C_t = 0{-}0.1$).

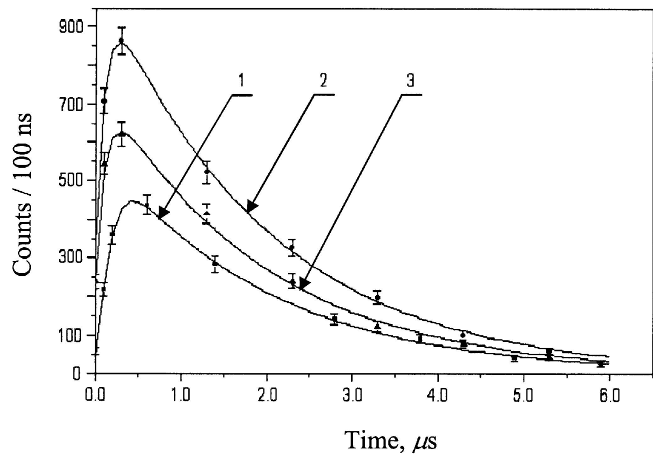


Fig. 5. The time distributions of pt fusion γ quanta for three different values of tritium concentrations: 1: $C_t = 5\times10^{-4}$; 2: $C_t = 6\times10^{-2}$; 3: $C_t = 1\times10^{-1}$. The solid lines are the result of fitting of the simulated time spectra. The indicated bars are the statistics errors.

As input data, the following values were used:

$$N_{\mu\text{stop}} = 10^4 \text{ s}^{-1} \text{ [43]};\ \varepsilon_\gamma = 2\times10^{-5};\ \varepsilon_\mu = 5\times10^{-4};\ \lambda_{pt\mu} = 7.5\times10^6 \text{ s}^{-1} \text{ [16]};$$

$$\lambda_{f,\gamma}^{pt}(I=1) = \lambda_f^{pt}(I=1) = 7\times10^4 \text{ s}^{-1} \text{ [16,19]};$$
$$\lambda_{f,\mu}^{pt}(I=0) = 5\times10^2 \text{ s}^{-1} \text{ [19]};\ \lambda_{tt\mu} = 1.8\times10^6 \text{ s}^{-1} \text{ [28]};$$

$$\lambda_{pt} = 9.3\times10^9 \text{ s}^{-1} \text{ [16]};\ \lambda_{10} = 1.0\times10^9 \text{ s}^{-1} \text{ [16]};\ \varphi = 1.0;\ C_t = 0{-}0.10.$$

For the purpose of choosing optimal experimental conditions, it was assumed that the total time of exposure for three different tritium concentrations was 700 h.

The time for each of three exposures is determined as:

$$t_1 : t_2 : t_3 = \sqrt{n_\gamma^{(3)}} : \sqrt{n_\gamma^{(2)}} : \sqrt{n_\gamma^{(1)}},$$

where $n_\gamma^{(1)}$, $n_\gamma^{(2)}$, $n_\gamma^{(3)}$ are the yields of γ quanta per one second in the exposures 1–3, respectively.

As a result of the combined χ^2 analysis of the calculated six time distributions of γ quanta and conversion muons (the Monte Carlo method was used for each of the three exposures for obtains the simulated experimental time distributions of γ quanta and conversion muon), we have found three optimal values of tritium concentrations[3]: $C_t = 5\times10^{-4}$, 6×10^{-2}, 1×10^{-1}.

Figures 5 and 6 show the calculated time distributions of the detected γ quanta with energy 19.8 MeV and conversion muons for three chosen tritium concentrations. Figure 7 shows the dependences of calculated parameter errors as a function of the statistic of detected events.

[3] The minimum of χ^2 for different combinations of three tritium concentrations corresponds to the chosen set of three C_t.

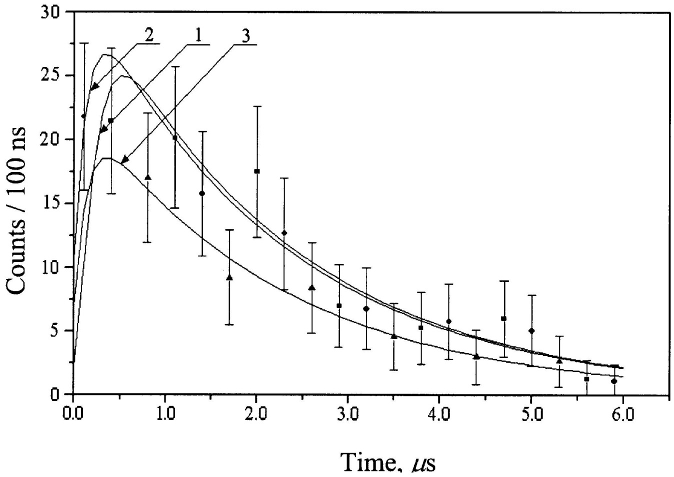


Fig. 6. Conversion muon time spectra for three chosen tritium concentrations: 1: $C_t = 5 \times 10^{-4}$; 2: $C_t = 6 \times 10^{-2}$; 3: $C_t = 1 \times 10^{-1}$. The solid lines are the result of fitting of the simulated time spectra. The indicated bars are the statistics errors.

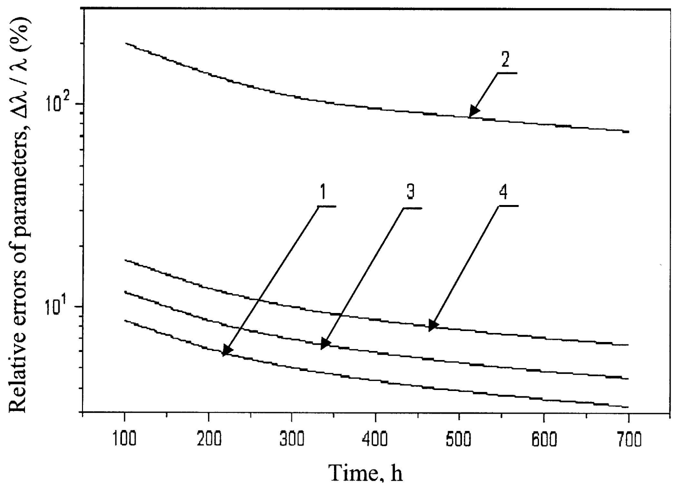


Fig. 7. Relative errors of $\lambda_{pt\mu}$, λ_{10}, $\lambda^{pt}_{f,\gamma}(I = 1)$ and λ_{pt} as a function of the statistics gathering time (ε_γ, ε_μ, $\lambda_{pt\mu}$, λ_{10}, λ_{pt}, $\lambda^{pt}_{f,\gamma}(I = 1)$ are the variable parameters; $\lambda^{pt}_{f,\mu}(I = 0) = 5 \times 10^2$ s^{-1}): 1: $\Delta\lambda_{pt}/\lambda_{pt}$; 2: $\Delta\lambda_{10}/\lambda_{10}$; 3: $\Delta\lambda_{pt\mu}/\lambda_{pt\mu}$; 4: $\Delta\lambda^{pt}_{f,\gamma}(I = 1)/\lambda^{pt}_{f,\gamma}(I = 1)$.

These parameter error dependences correspond to the approximation of the simulated γ quanta and conversion muon experimental time distributions by the expressions (11–14) with unknown parameters ε_γ, ε_μ, $\lambda_{pt\mu}$, λ_{10}, λ_{pt}, $\lambda^{pt}_{f,\gamma}(I = 1)$. It should be pointed out that in such case the $\lambda^{pt}_{f,\mu}(I = 0)$ was fixed and equal 5×10^2 s^{-1} [19].

As seen, the sufficient total time of statistics gathering for determination $\lambda_{pt\mu}$, $\lambda^{pt}_{f,\gamma}(I = 1)$, λ_{pt} parameters with accuracy of $\sim$10% is $\sim$300 hours.

As for transition rate between hyperfine level of $t\mu$ atom λ_{10} (curve 2 in Fig. 7) the uncertainty of this magnitude is $\sim$100% for the same time gathering statistics. At the statistics gathering time of 600 h the accuracy of λ_{10} falls to 75%.

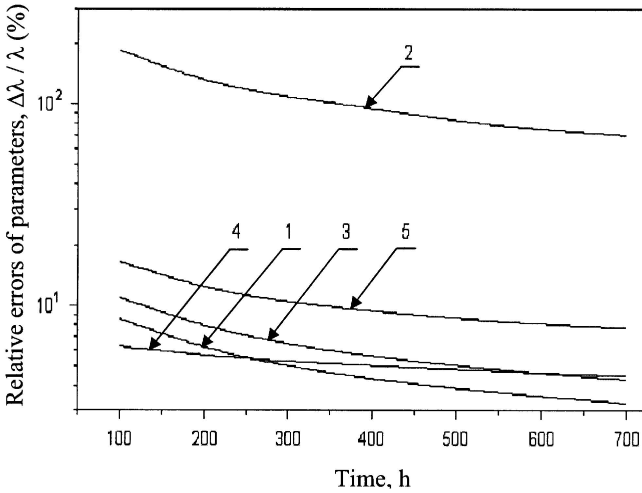


Fig. 8. The dependences of the μCF parameter relative errors from statistic gathering time (ε_γ and ε_μ are know from additional experiment). The numbers 1–4 at curves correspond to the Figure 7; 5: $\Delta\lambda^{pt}_{f,\mu}(I = 0)/\lambda^{pt}_{f,\mu}(I = 0)$.

From the proceeding it may be seen that the result of joint analysis of γ quanta and conversion muon time distributions received at three chosen tritium concentrations is weakly sensitive to the value of λ_{10}.

More precise measurement of λ_{10} is possible at essential increasing of the collection statistics and the range of variation of H-T mixture density and tritium concentration.

The next step of the μCF parameter errors calculation has been done setting ε_γ and ε_μ are know with accuracy of 5% from additional experiments. The results of these calculations are presented in Figure 8. As seen, it is appeared the possibility to determine for the first time the information about fusion rate $\lambda^{pt}_{f,\mu}(I = 0)$. This circumstance is very important for correct description of the pt reaction mechanism. The relative errors of other μCF parameters in H-T mixture at this optimization less than the corresponding values from previous optimization at the same gathering times of statistics.

From the presented analysis of the μCF kinetic in the H-T mixture, one can conclude that from the experiment performed for three different tritium concentrations, the unknown parameters of muon catalyzed ($\lambda_{pt\mu}$, $\lambda^{pt}_{f,\gamma}(I = 1)$, λ_{pt}) fusion can be obtained with sufficient accuracy. Simultaneous measurement of yields and time distributions of γ quanta and conversion muons will allow one not only to find the ratio of probabilities for the radiation and non radiation channel of pt reaction, but also their exact values. So the possibility exists to measure the fusion rate occurred in the ground state of the $pt\mu$ molecule due to EO and Ml transitions with the conversion of muons and γ quanta, respectively.

The measurement of γ quanta and conversion muon efficiencies in the additional experiments will allow to obtain the value of $\lambda^{pt}_{f,\mu}(I = 0)$ and to decrease the relative errors of μCF parameters such as $\lambda_{pt\mu}$, λ_{10}, λ_{pt}, $\lambda^{pt}_{f,\gamma}(I = 1)$.

In addition, the accuracy of λ_{10} can be improved due to the measurement and joint analysis of γ quanta, conversion muon and Auger electrons emitted at deexcitation of $pt\mu$ molecules formed in $(J\nu) = (10)$ state.

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Appendix A: The probabilities of ptμ formation

$$W_{pt\mu}^{F=0}(\mathsf{J}=1/2^*; I=1) = a_{00}^{1/2^*}(\uparrow\downarrow)\, W_{1/2^*}^{1} = 3.7\times10^{-3};$$

$$W_{pt\mu}^{F=0}(\mathsf{J}=1/2; I=1) = a_{00}^{1/2}(\uparrow\downarrow)\, W_{1/2}^{1} = 8.59\times10^{-1};$$

$$W_{pt\mu}^{F=0}(\mathsf{J}=1/2; 1/2^*; I=1) = W_{pt\mu}^{F=0}(\mathsf{J}=1/2^*; I=1) + W_{pt\mu}^{F=0}(\mathsf{J}=1/2; I=1) = 8.62\times10^{-1};$$

$$W_{pt\mu}^{F=1}(\mathsf{J}=1/2; I=1) = a_{00}^{1/2}(\uparrow\uparrow)\, W_{1/2}^{1} = 3.6\times10^{-2};$$

$$W_{pt\mu}^{F=1}(\mathsf{J}=1/2^*; I=1) = a_{00}^{1/2}(\uparrow\uparrow)\, W_{1/2^*}^{1} = 9.8\times10^{-3};$$

$$W_{pt\mu}^{F=1}(\mathsf{J}=1/2; 1/2^*; I=1) = W_{pt\mu}^{F=1}(\mathsf{J}=1/2; I=1) + W_{pt\mu}^{F=1}(\mathsf{J}=1/2^*; I=1) = 4.58\times10^{-2};$$

$$W_{pt\mu}^{F=1}(\mathsf{J}=3/2; I=1) = a_{00}^{3/2}(\uparrow\uparrow)\, W_{3/2}^{1} = 6.67\times10^{-1};$$

$$W_{pt\mu}^{F=1}(\mathsf{J}=3/2; 1/2^*; 1/2; I=1) = 7.13\times10^{-1};$$

$$W_{pt\mu}^{F=1}(\mathsf{J}=1/2; I=0) = a_{00}^{1/2}(\uparrow\uparrow)\, W_{1/2}^{0} = 1.22\times10^{-3};$$

$$W_{pt\mu}^{F=1}(\mathsf{J}=1/2^*; I=0) = a_{00}^{1/2^*}(\uparrow\uparrow)\, W_{1/2^*}^{0} = 0.286;$$

$$W_{pt\mu}^{F=0}(\mathsf{J}=1/2; I=0) = a_{00}^{1/2}(\uparrow\downarrow)\, W_{1/2}^{0} = 2.93\times10^{-2};$$

$$W_{pt\mu}^{F=0}(\mathsf{J}=1/2^*; I=0) = a_{00}^{1/2^*}(\uparrow\downarrow)\, W_{1/2}^{0} = 0.108,$$

where $W_{pt\mu}^{F}(\mathsf{J}, I)$ is the probability of a $pt\mu$ formation in the state with total angular momentum J and nuclear spin I in the collisions of a $t\mu$ atom with a spin F and H_2 molecule.

Appendix B: The coefficients A_1^γ–A_4^γ and A_1^η–A_5^μ

$$A_1^\gamma = A\left(\frac{1}{\lambda_1-\lambda_2}\left(\frac{k+l+m}{\lambda_1-\lambda_4}\right) + \frac{1}{\lambda_1-\lambda_3}\left(\frac{n+p}{\lambda_1-\lambda_4}\right)\left(\frac{1}{3}-\frac{\lambda_{10}\varphi C_t}{\lambda_1-\lambda_2}\right)\right),$$

$$A_2^\gamma = -\frac{A}{(\lambda_1-\lambda_2)(\lambda_2-\lambda_4)} \times \left((k+l+m) - \frac{\lambda_{10}\varphi C_t}{\lambda_2-\lambda_3}(n+p)\right),$$

$$A_3^\gamma = -\frac{A}{\lambda_1-\lambda_3}\left(\frac{n+p}{\lambda_3-\lambda_4}\right)\left(\frac{1}{3}+\frac{\lambda_{10}\varphi C_t}{\lambda_2-\lambda_3}\right),$$

$$A_4^\lambda = \frac{A}{\lambda_1-\lambda_4}\left(\frac{k+l+m}{\lambda_2-\lambda_4} + \frac{n+p}{\lambda_3-\lambda_4}\left(\frac{1}{3}+\frac{\lambda_{10}\varphi C_t}{\lambda_2-\lambda_4}\right)\right),$$

$$A = \frac{3}{4}N_{\mu\mathrm{stop}}(\lambda_{pt}\varphi C_t)(\lambda_{pt\mu}\varphi C_p)\lambda_{f,\gamma}^{pt}(I=1)\,\varepsilon_\gamma,$$

$$k = W_{pt\mu}^{F=1}(\mathsf{J}=3/2; I=1) = 6.67\times10^{-1},$$

$$l = W_{pt\mu}^{F=1}(\mathsf{J}=1/2; I=1) = 3.6\times10^{-2},$$

$$m = W_{pt\mu}^{F=1}(\mathsf{J}=1/2^*; I=1) = 9.8\times10^{-3},$$

$$n = W_{pt\mu}^{F=0}(\mathsf{J}=1/2; I=1) = 8.59\times10^{-1},$$

$$p = W_{pt\mu}^{F=0}(\mathsf{J}=1/2^*; I=1) = 3.7\times10^{-3},$$

$$A_1^\mu = A_1\left(\frac{1}{\lambda_1-\lambda_2}\left(\frac{\lambda_{f,\mu}^{pt}(I=1)}{\lambda_1-\lambda_4}(k+l+m) + \frac{\lambda_{f,\mu}^{pt}(I=0)}{\lambda_1-\lambda_0}(r+s)\right) + \left(\frac{1}{3}-\frac{\lambda_{10}\varphi C_t}{\lambda_1-\lambda_2}\right)\frac{1}{\lambda_1-\lambda_3} \times \left(\frac{\lambda_{f,\mu}^{pt}(I=1)}{\lambda_1-\lambda_4}(n+p) + \frac{\lambda_{f,\mu}^{pt}(I=0)}{\lambda_1-\lambda_0}(t+u)\right)\right),$$

$$A_2^\mu = -\frac{A_1}{\lambda_1-\lambda_2}\left(\frac{\lambda_{f,\mu}^{pt}(I=1)}{\lambda_2-\lambda_4}(k+l+m) + \frac{\lambda_{f,\mu}^{pt}(I=0)}{\lambda_2-\lambda_0}(r+s) - \frac{\lambda_{10}\varphi C_t}{\lambda_2-\lambda_3}\left(\frac{\lambda_{f,\mu}^{pt}(I=1)}{\lambda_2-\lambda_4}(n+p) + \frac{\lambda_{f,\mu}^{pt}(I=0)}{\lambda_2-\lambda_0}(t+u)\right)\right),$$

$$A_3^\mu = -\frac{A_1}{\lambda_1 - \lambda_3}\left(\frac{\lambda_{f,\mu}^{pt}(I=1)}{\lambda_3-\lambda_4}(n+p) + \frac{\lambda_{f,\mu}^{pt}(I=0)}{\lambda_3-\lambda_0}(t+u)\right)\left(\frac{1}{3}+\frac{\lambda_{10}\varphi C_t}{\lambda_2-\lambda_3}\right),$$

$$A_4^\mu = \frac{A_1\,\lambda_{f,\mu}^{pt}(I=1)}{\lambda_1-\lambda_4}\left[\frac{1}{\lambda_2-\lambda_4}(k+l+m) + \frac{1}{\lambda_3-\lambda_4}(n+p)\left(\frac{1}{3}+\frac{\lambda_{10}\varphi C_t}{\lambda_2-\lambda_4}\right)\right],$$

$$A_5^\mu = \frac{A_1\,\lambda_{f,\mu}^{pt}(I=0)}{\lambda_1-\lambda_0}\left[\frac{r+s}{\lambda_2-\lambda_0} + \frac{t+u}{\lambda_3-\lambda_0}\left(\frac{1}{3}+\frac{\lambda_{10}\varphi C_t}{\lambda_2-\lambda_0}\right)\right],$$

$$A_1 = \frac{3}{4}N_{\mu\mathrm{stop}}\,\lambda_{pt}\varphi C_t\,\lambda_{pt\mu}\varphi C_p\,\varepsilon_\mu,$$

$$r = W_{pt\mu}^{F=1}\left(\mathsf{J}=\frac{1}{2};I=0\right) = 1.22\times10^{-3},$$

$$s = W_{pt\mu}^{F=1}(\mathsf{J}=1/2^*;I=0) = 0.286,$$

$$t = W_{pt\mu}^{F=0}\left(\mathsf{J}=\frac{1}{2};I=0\right) = 2.93\times10^{-2},$$

$$u = W_{pt\mu}^{F=0}(\mathsf{J}=1/2^*;I=0) = 0.108,$$

where $N_{\mu\mathrm{stop}}$ is the number of muons stopped in the H-T mixture; ε_γ, ε_μ are the efficiencies of the detection of γ quanta from reactions (9a–9d) and conversion muons from (9e), respectively.

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