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Full Length Research Paper

Muon catalyzed fusion in the target H-T/D_2/H-D by taking fast muon conversion

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In past years, two/three-layer hydrogen targets with a composition of H/D/T at temperature ~3K have been studied for muon catalyzed fusion. Several theoretical and experimental studies have evaluated that the conversion efficiency of fast muons in such targets is very low. Here, the muon cycling coefficient has been determined for the heterogeneous target of $H-T/D_2/H-D$ by taking the conversion efficiency of incident muons of momentum 26.25 MeV/c. This parameter extremely affects the muon cycling coefficient by the reason of slow muon cycles in the third layer of $H-D$. The optimal muon cycling coefficient equals 87.5.

Key words: Three-layer target, condensed hydrogen-deuterium layer, muon cycling coefficient, fast muon.

INTRODUCTION

The negative muon is a lepton of the second generation with the mass about 207 times larger than that of electron, and has a mean life time $\tau_\mu = \lambda_0^{-1} = 2.198 \mu s$. The λ_0 is the muon decay rate. The negative muon can tightly be bounded as a muonic atom. Such a muon can participate in a variety of atomic and molecular processes. Muon dynamics in muon catalyzed fusion (μCF) includes very complicated processes, such as muonic interactions which can take place in hydrogen, can be recognized as muonic atom formation, elastic scattering, inelastic scattering, muonic molecular formation, fusion and sticking (Mulhauser et al., 2001). A muonic atom during collision with usual atoms and molecules can form a muonic molecule. The latter in turn can result in fusion reactions between nuclei (Froelich, 1992; Markushin, 1994). When the muonic atom μx (where x denotes one of the hydrogen isotopes p, d, t) collides with molecules like H_2, HD, DT, T_2 or D_2, it forms muonic molecules, such as ddμ, ttμ, dtμ, ppμ, pdμ and ptμ. The muon is probably released after nuclear fusion, and can repeat the same processes. This paper considers a multilayered solid target and describes the atomic and nuclear processes. The fast muon conversion and hydrogen solid effect are taken into account for estimation of the muon cycling coefficient in the heterogeneous target $H-T/D_2/H-D$.

MUON CATALYZED FUSION IN SUGGESTED MULTILAYERED CONDENSED SYSTEM

A scheme of the suggested heterogeneous solid target $H-T/D_2/H-D$ is as shown in Figure 1. Muons of momentum 26.25 MeV/c are injected into the $H-T$ layer. In this layer, after muon stops at a distance of about 0.4 mm, muon cascade reactions will begin (Wozniak et al., 2003; Marshall et al., 1999). Once a negative muon enters the first layer with small admixture of tritium, μp atoms are formed rapidly due to many

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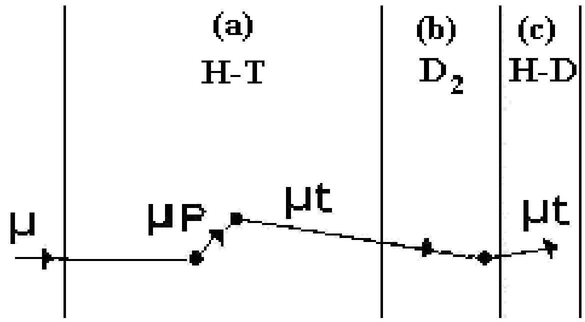

Figure 1. Muons of momentum 26.25 MeV/c are injected into the multilayered solid target $H-T/D_2/H-D$. The μt emission is based on the RT effect: (a) the H/T layer adopted with a small amount tritium impurity for production of fast muonic atoms, (b) deuterium moderator, (c) a fusion layer of $H-D$. The most of released muons by fusion stay in the fusion layer.

proton nuclei with a concentration of $c_{p_0} \cong 0.999$. The de-excitation of μp to the ground state competes with isotopic muon transfer:

$$\mu p_{nl} + t, p \to \mu p_{n'l'} + t, p \qquad (1)$$

$$\mu p_{1s} + t \to \mu t_{1s} + p + 183eV \qquad (2)$$

The $n, l(n', l')$ are principal and angular momentum quantum numbers, respectively. As the reaction (Equation 2) takes place in the H-T layer with a relative density of $\phi_0 = 1.2$, the μp atoms are de-excited rapidly (ϕ_0 is measured relative to the density of liquid hydrogen). In the reaction (Equation 2), the kinetic energy of μt_{1s} atom is about 45 eV. After μt formation in the H-T layer, muonized protium-tritium (μpt) and muonized tritium-tritium (μtt) molecules are probably formed:

$$\begin{cases} \mu t + p \xrightarrow{\lambda_{pt\mu}} pt\mu \\ \mu t + t \xrightarrow{\lambda_{tt\mu}} tt\mu \end{cases} \qquad (3)$$

Their corresponding formation rates ($\lambda_{pt\mu}, \lambda_{tt\mu}$) are about 10^6 s^{-1} (Markushin, 1994). These fusion rates ($\lambda^f_{pt\mu}, \lambda^f_{tt\mu}$) are relatively low. Due to very small concentration of tritium ($c_t = 0.12\%$) and eventually low molecular formation rates which were mentioned earlier, these processes do not make a significant effect on the μt_{1s} population. By the help of Ramsauer-Townsend (RT) effect (Mulhauser et al., 2006), μt_{1s} atoms escape from the H-T layer. A thickness of $\approx 800 \mu m$ has been chosen for this layer. This muonic atom, during collisions in the D_2 layer with $\approx 5\mu m$ thick, behaves as a heavy neutron because it is neutral, very tightly bound and very small as compared to usual molecules. Hence, it makes slowing down in the D_2 rapidly. During a collision in the H-D layer with a relative density of $\phi = 1.45$ and $\approx 1\mu m$ thickness, depending on deuterium concentration, a μdt muonic molecule can be formed resonantly (Vesman, 1967; Gheisari, 2010):

$$\mu t_{1s} + D_2 \to [(\mu dt)dee] \qquad (4)$$

The deuterium/proton concentrations in the H/D layer are shown with the notations c_d and c_p, respectively. The fusion will occur in μdt with a rate of $\lambda^f_{dt\mu} = 1.1 \times 10^{12} s^{-1}$:

$$\mu dt \xrightarrow{\lambda^f_{dt\mu}} \begin{cases} \alpha + n + \mu^- + 17.6MeV \ (1-\omega_s^{eff}) \\ \mu\alpha + n + 17.6MeV \ (\omega_s^{eff}) \end{cases} \qquad (5)$$

The muon can be released with a probability of $1-\omega_s^{eff}$. By interactions with hydrogen/deuterium will make the following reactions (Markushin, 1995; Filipowicz et al., 2008):

$$\begin{cases} \mu^- + H \xrightarrow{\lambda_a} \mu p + e^- \\ \mu^- + D \xrightarrow{\lambda_a} \mu d + e^- \\ \mu p + d \xrightarrow{\lambda_{pd}} \mu d + p \\ \mu d^F + p \xrightarrow{\lambda_{pd\mu}} pd\mu_{J\upsilon} \\ \mu d^F + d \xrightarrow{\lambda^F_{dd\mu}} dd\mu \end{cases} \qquad (6)$$

λ_a is the muonic atom formation rate, and $\lambda_{pd\mu}$ ($\lambda^F_{dd\mu}$) being the formation rate of $pd\mu$ ($dd\mu$). F denotes the spin state of the μd atom. The rate of ddμ molecule formation for F=3/2(1/2) is $\lambda^{3/2}_{dd\mu}$ ($\lambda^{1/2}_{dd\mu}$). The muon can transfer from proton to deuterium by the rate of λ_{pd}. The fusion of $pd\mu$ molecule with a rate of $\lambda^f_{pd\mu}$ in the H-D layer is through the following channels (Filipowicz et al., 2008):

$$pd\mu_{J,\upsilon} \rightarrow \begin{cases} {}^3_2He + \mu + 5.5MeV \quad (\lambda_J^{\mu}) \\ {}^3_2He\mu + \gamma + 5.5MeV \; (\lambda_J^{\gamma}) \end{cases} \tag{7}$$

where J is the total angular momentum and υ the vibration-quantum number of the $pd\mu$ molecule. The fusion of $dd\mu$ molecule with a rate of $\lambda^f_{dd\mu}$ is through the following reactions:

$$dd\mu \xrightarrow{(1-0.58\omega_{dd})\lambda^f_{dd\mu}} \begin{cases} {}^3_2He + n + \mu + 3.3MeV \\ p + t + \mu + 4.04MeV \end{cases} \tag{8}$$

The muon is captured with the effective probability of $0.58\omega_{dd}$, where ω_{dd} equals 12%. As the aforementioned, the resonant formation of μdt occurs in the last layer. The released muons in the H/D layer can be captured by proton/deuterium nuclei and then form muonic molecules again and stay in the same layer with very high probability (Gheisari, 2010, 2011; Bakule and Morenzoni, 2004). Naturally, during mean life time of muon, all of these processes compete with each other. On this base, the following rate of equations is written for the populations of the particles:

$$\frac{dN^0_{\mu}(t)}{dt} = -\lambda_0 N^0_{\mu}(t) - \phi_0 \lambda_a N^0_{\mu}(t) \tag{9}$$

$$\frac{dN^0{}_{\mu p}(t)}{dt} = -\lambda_0 N^0{}_{\mu p}(t) + c_{p0}\phi_0\lambda_a N^0_{\mu}(t) - c_t\phi_0\lambda_{pt}N^0{}_{\mu p}(t) - c_{p0}\phi_0\lambda_{\mu pp}N^0{}_{\mu p}(t) \tag{10}$$

$$\frac{dN^0{}_{\mu t}(t)}{dt} = -\lambda_0 N^0{}_{\mu t}(t) + c_t\phi_0\lambda_a N^0_{\mu}(t) - c_{p0}\phi_0\lambda_{\mu pt}N^0{}_{\mu t}(t) + c_t\phi_0\lambda_{pt}N^0{}_{\mu p}(t) \\ - c_t\phi_0\lambda_{\mu tt}N^0{}_{\mu t}(t) \tag{11}$$

$$\frac{dN^0{}_{\mu tt}(t)}{dt} = -\lambda_0 N^0{}_{\mu tt}(t) - \lambda^f_{\mu tt}N^0{}_{\mu tt}(t) + c_t\phi_0\lambda_{\mu tt}N^0{}_{\mu t}(t) \tag{12}$$

$$\frac{dN^0{}_{\mu pt}(t)}{dt} = -\lambda_0 N^0{}_{\mu pt}(t) - \lambda^f_{\mu pt}N^0{}_{\mu pt}(t) + c_p\phi_0\lambda_{\mu pt}N^0{}_{\mu t}(t) \tag{13}$$

$$\frac{dN_{\mu dt}(t)}{dt} = -\lambda_0 N_{\mu dt}(t) + c_d\phi\lambda^{res}_{\mu dt}N^{tr}_{\mu t}(t) - \lambda^f_{\mu dt}N_{\mu dt}(t) \tag{14}$$

$$\frac{dN_{\mu p}(t)}{dt} = -\lambda_0 N_{\mu p}(t) + c_p\phi\lambda_a N_{\mu}(t) - c_p\phi\lambda_{\mu pp}N_{\mu p}(t) - c_d\phi\lambda_{pd}N_{\mu p}(t) \tag{15}$$

$$\frac{dN_{\mu d^{1/2}}(t)}{dt} = \frac{1}{3}c_d\phi\lambda_a N_{\mu}(t) + \frac{1}{3}c_d\phi\lambda_{pd}N_{\mu p}(t) - c_d\phi\lambda^{1/2}_{\mu dd}N_{\mu d^{1/2}}(t) + c_d\phi\lambda_d N_{\mu d^{3/2}}(t) \\ - c_p\phi\lambda_{\mu pd}N_{\mu d^{1/2}}(t) - \lambda_0 N_{\mu d^{1/2}}(t) \tag{16}$$

$$\frac{dN_{\mu d^{3/2}}(t)}{dt} = \frac{2}{3}c_d\phi\lambda_a N_{\mu}(t) + \frac{2}{3}c_d\phi\lambda_{pd}N_{\mu p}(t) - c_d\phi\lambda^{3/2}_{\mu dd}N_{\mu d^{3/2}}(t) - c_p\phi\lambda_{\mu pd}N_{\mu d^{3/2}}(t) \\ - c_d\phi\lambda_d N_{\mu d^{3/2}}(t) - \lambda_0 N_{\mu d^{3/2}}(t) \tag{17}$$

$$\frac{dN_{\mu}(t)}{dt} = -\lambda_0 N_{\mu}(t) + \lambda^f_{\mu dt}(1-\omega^{eff}_s)N_{\mu dt}(t) + \lambda^f_{\mu pt}(1-\omega_{pt})N_{\mu pt}(t) - \lambda_a\phi N_{\mu}(t) \\ + \lambda^f_{\mu dd}(1-0.58\omega_{dd})N_{\mu dd}(t) \tag{18}$$

Table 1. The different values of the muon cycling coefficient at a temperature of about 3K.

c_p	χ_c
0.001	87.5
0.01	87
0.1	80
0.2	72
0.25	68
0.3	64
0.4	55
0.5	45
0.6	36
0.7	27
0.75	22
0.8	17.5
0.85	12.6
0.9	8.8
0.98	1.8
0.99	0.88
0.995	0.46

The notation χ_c represents the muon cycling coefficient.

$$\frac{dN_{\mu pt}(t)}{dt} = -\lambda_0 N_{\mu pt}(t) - \lambda^f_{\mu pt} N_{\mu pt}(t) + c_p \phi \lambda_{\mu pt} N^{tr}_{\mu t}(t) \quad (19)$$

$$\frac{d\chi_\mu(t)}{dt} = \lambda^f_{\mu dt} N_{\mu dt}(t) + \lambda^f_{\mu pt} N_{\mu pt}(t) + \lambda^f_{dd\mu} N_{dd\mu}(t) \quad (20)$$

$$\frac{dN_{\mu dd}(t)}{dt} = -\lambda_0 N_{\mu dd}(t) - \lambda^f_{\mu dd} N_{\mu dd}(t) + c_d \phi \lambda^{3/2}_{\mu dd} N_{\mu d^{3/2}}(t) \quad (21)$$

where $N^{tr}_{\mu t}(t)$ denotes a time population of fast μt_{1s} atoms which enter the third layer (Gheisari, 2011). The notations $N^0_{()}(t)$ and $N_{()}(t)$ represent the time populations of muon and muonic atoms/molecules in the first and third layers, respectively. The value of $\chi_\mu(t)$ at $t = 2.2\mu s$ denotes the muon cycling coefficient (χ_c). The results of this coefficient are presented in Table 1. It is necessary to mention that the tritium impurity $c_t = 0.12\%$, the values of the relative densities (φ_0 = 1.2, φ = 1.43), and the rates have been extracted from the literature data (Markushin, 1995; Filipowicz et al., 2008; Gheisari, 2011; Adamczak and Faifman, 2005; Mulhauser et al., 2006) and muon sticking probabilities (Mulhauser et al., 2001).

DISCUSSION

In this work, we have tried to study muon catalyzed fusion in the heterogeneous target $H-T/D_2/H-D$ using incident muons of momentum 26.25 MeV/c. The target has been assumed to be at low temperature. After injection of such fast muons into the H-T layer, a large fraction of μt_{1s} atoms leave the layer by help of RT effect. The RT effect has significantly been observed in solid hydrogen targets adopted with a small amount of tritium. We have taken $c_t = 0.12\%$ for the composition of the first layer. After slowing down of μt_{1s} atoms through D_2 layer, $dt\mu$ molecules are formed resonantly in the $H-D$ layer. The released muons can form other muonic molecules, leading to fusion. The leakage of muons from the condensed H/D layer is low. On this base, we used only three hydrogen layers. The rate of Equations 9 to 21 has been written for description of such processes in muon catalyzed fusion. Our equations have been solved by using Lsode computer code for different deuterium concentrations in the last layer. Our results show that the muon cycling coefficient (χ_c) in the fusion layer equals 87.5 under condition that we take $c_p = 0.001$. Due to high muon sticking probability in the reaction (Equation 7), the fusion yield of $pd\mu$ has been neglected for estimation of χ_c.

The maximum value of the muon cycling coefficient in the fusion layer equals 88. The differences between the muon cycling coefficients in a low range of deuterium ($c_d \leq 2\%$) reduces with increasing proton concentration. This may be by the reason of slow variation of the initial population of the $d\mu^{3/2}$ in the spin-flip interaction. The deceleration of dμ muonic atom below the Debye energy is very slow, and that mean energy of $d\mu^{3/2}$ atom is always significantly greater than 1 meV in pure deuterium (Adamczak and Faifman, 2005). By this reason, we have used the $dd\mu$ formation rate calculated by Adamczak et al. (1991, 2003). As an error estimation, the validity of the present results is more for low proton concentrations.

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