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Archives

Probing the Nature of Sticking in Muon Catalyzed Fusion
with Laminated Targets

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Abstract

The importance of muon losses due to slow side channels or impurities compared to muon sticking to fusion α -particles can be measured using laminated targets and suitable trigger conditions for detecting fusion neutrons. Such targets can consist of a deuterium-tritium filled cavity with many layers of thin metal foils. Muons that have been captured by a fusion α -particle are with high probability carried to the foils and can thus be experimentally separated from other lost muons.

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Recent progress in muon catalyzed fusion research [1] [2] has caused a renewed interest in the possibility of energy applications [3] [4] [5]. In order to increase the fusion yield significantly we must, however, obtain a detailed understanding of all sources of muon loss. The main muon loss mechanism is thought to be μ^- sticking to a fusion α -particle [6]. Measured muon losses could apart from α -sticking consist of muon losses to various side channels where the muon is scavenged by impurities or captured in other passive states [7]. The muon loss per fusion cycle in a "infinitely" large target can be written,

$$(1) \quad \omega = \omega_h + (1 - R_0)\omega_s^0 + \omega_0$$

where ω_h is the probability for muon loss to a side channel, ω_s^0 is the initial α -sticking probability after a deuterium-tritium catalyzed fusion reaction, $R_0 \approx 24\%$ [8] is the probability that the muon is collisionally stripped from the α -particle and thus reactivated and ω_0 is the probability for natural muon decay during the cycle.

In a finite target fusion $\alpha\mu$ -atoms may hit the walls of the target container and other muonic atoms or molecules may reach the walls by diffusion. The muon will then with high probability be captured by a heavy nucleus in a weak absorption reaction ($p + \mu^- \rightarrow \nu + n$). The muon lifetime in the target wall is typically at least one order of magnitude smaller than the natural muon lifetime [9].

Using standard expressions [10] for proton stopping power within the proper velocity range we find that the projected range of a fusion $\alpha\mu$ atom is $\lambda = 3.6 \times 10^{-2} \phi^{-1}$ cm where ϕ is the target density in units of the liquid

hydrogen density (4.25×10^{22} atoms/cm³). The range of free fusion muons are much smaller than λ .

In experiments where fusion neutrons are detected one can in principle use one of two trigger conditions; A) only fusion neutrons in coincidence with a muon decay electron are accepted B) all fusion neutrons are accepted. By using a target that is small compared to λ together with trigger condition (A) we can discriminate against true α -sticking and thus by comparing to measurements with a large target vessel separately measure ω_h in eq. (1). Coincidence conditions such as (A) are routinely used in present experiments [1] [2] [11] [12] (with target dimensions $\gg \lambda$) to suppress background from beam muon wall stops.

Consider an experimental sample of catalyzed fusion cycles where each cycle starts with the emission of a fusion neutron and ends with probabilities as indicated in one of the following conditions 1) the muon is free to begin the next cycle (p'_f) 2) the muon decays during the cycle (ω_0) 3) the muon is captured in a passive state and decays eventually thus emitting a fast electron (p_e) 4) the muon enters a passive state and is absorbed with emission of a neutrino (p_a). Using trigger condition (A) we will suppress cycles that end in condition (4). The conditional probability for muon loss in the remaining biased sample can be written

$$\omega = (p_e + \omega_0)/(1 - p_a).$$

Measured muon loss probabilities are usually presented with the loss due to natural muon decay during the cycle subtracted. The corresponding quantity for our biased sample is

$$(2) \quad \omega_{\text{eff}} = p_e/(1 - p_a) + \omega_0 p_a/(1 - p_a).$$

The various muon loss channels in a small target are shown in Fig. 1. Both $\alpha\mu$ wall hits and diffusion effects are taken into account. Each loss channel ends in one of the four final state categories given above. The probabilities for muon loss leading to muon decay (p_e) and absorption (p_a) are according to Fig. 1:

$$(3) \quad p_e = \omega_h(1 - d_h) + \kappa\omega_s + \beta p_w$$

$$(4) \quad p_a = (1 - \beta)p_w$$

where the wall hit probability is

$$p_w = \delta_f + \omega_h d_h + (1 - R_{\text{eff}} - \kappa)\omega_s$$

We shall now consider the effect of $\alpha\mu$ -atoms reaching the walls and later discuss diffusion corrections. The factor κ in eq. (3) and (4) is given by

$$(5) \quad \kappa = \int P_s(\vec{r}, \Omega) \frac{d^3r d\Omega}{4\pi V}.$$

where $p_s(\vec{r}, \Omega)$ is the probability for the muon to remain bound to the α -particle until it decays given that a fusion $\alpha\mu$ -atom is emitted from a point $\vec{r}$ in direction Ω . We assume here that the muon stop probability is uniform within the target volume V . The integrand in (5) is the product of the probability that the muon is not regenerated and do not hit the walls:

$$(6) \quad p_s(\Omega, \vec{r}) = [1 - R(d)][(1 - \Theta(\ell - d))]$$

where $d(\vec{r}, \Omega)$ is the distance to the target wall and $\Theta(\ell-d)$ is the probability to hit the target wall ($\Theta(x)=1$ for $x>0$ and $\Theta(x)=0$ for $x<0$).

Inserting (6) in (5) we find,

$$(7) \quad \kappa = (1 - R_0)(1 - G)$$

The average wall hit probability is

$$(8) \quad G = \int \Theta(\ell - d(\vec{r}, \Omega)) \frac{d^3r d\Omega}{4\pi V}.$$

For a spherical target with radius $R = x\ell$ we find that $G = 3x^{-1}/4 - x^{-3}/16$ for $x>0.5$ and $G = 1$ for $x<0.5$. If the target consists of parallel infinite foils with interspacing $R = x\ell$ we get $G = 1 - x/2$ for $x<1$ and $G = 1/2x$ for $x>1$. These results are shown in Fig. 2. The average reactivation probability

$$(9) \quad R_{eff} = \int R(d(\vec{r}, \Omega)) \frac{d^3r d\Omega}{4\pi V}$$

is given in Fig. 3 for spherical and laminated targets. We have used the model of Bracci and Fiorentini [8] to obtain the reactivation probability $R(d)$ within the range d .

To estimate the diffusion corrections δ_f and d_h in Fig. 1 and eqs. (3) and (4) we consider the diffusion of ground-state $d\mu$ -atoms. The measured [13] $d\mu$ diffusion length ℓ_d (until muon decay) in deuterium is 0.54 cm at 10 atm pressure leading to $\ell_d = 6.8 \times 10^{-3} \Phi^{-1}$ cm = 0.2ℓ . Earlier measurements by Dzhelepov et al. [14] gives a shorter diffusion length. The diffusion length during a given fusion cycle is $\ell_c = (\lambda_0/\lambda_c)^{1/2} \ell_d \approx 6 \times 10^{-2} \Phi^{-1} \ell_d$ (at $\Phi=1$) where λ_0 and λ_c are the muon decay rate and the fusion cycle rate, respectively.

The probability for an active muon to reach the walls by diffusion during a given fusion cycle is $\delta_f = G(\lambda_c/r)$ where G is the geometrical function given in Fig. 2. A muon that has entered a slow side-channel would be bound in some atomic or molecular state. We can safely assume that the diffusion length during the muon lifetime is smaller than λ_d . The wall hit probability in the side channel is hence $d_h < G(\lambda_d/r)$.

A simple target for measuring ω_h could consist of a target cavity filled with DT-mixture and many layers of parallel gold foils. The construction of such laminated targets appears to be feasible at least for $\Phi < 1$. Gold leaf can be as thin as 10^{-5} cm! The predicted outcome of such an experiment is shown in Fig. 4 for various assumptions concerning ω_h . A foil interspacing of $r = 0.5\lambda$ would give the best resolution. If the observed muon loss is due to α -sticking one would with the $r = 0.5\lambda$ laminated target find that $\omega_{\text{eff}} = 0.17\%$ which is significantly different from expected result $\omega_{\text{eff}} = 0.5\% \pm 0.05\%$ if a slow side channel is the dominating source of muon loss.

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FIGURE CAPTIONS

Fig. 1. Muon losses caused by α -sticking ($\alpha\mu$) and slow side-channels (S.Ch.) are shown together with the probabilities for 1) $d\mu$ or $t\mu$ atoms to diffuse to the wall during the following cycle ($p_f\delta_f$) 2) muons in a side-channel to reach the wall by diffusion ($\omega_h d_h$) and 3) fusion $\alpha\mu$ atoms to hit the wall ($(1-R_{\text{eff}}-\kappa)\omega_s^\circ$). The probabilities for the muon to decay and thus produce a fast electron (e^-) after 1) α -sticking ($\kappa\omega_s^\circ$) 2) entering a side-channel ($\omega_h(1-d_h)$) 3) hitting the wall (βp_w) and 4) during a fusion cycle (λ_o/λ_c) are also displayed.

Fig. 2. The average probability for $\alpha\mu$ -atoms to hit the target wall for a spherical target and for a target consisting of parallel infinite foils. The target size is plotted in units of the $\alpha\mu$ range ℓ .

Fig. 3. The effective reactivation probability R_{eff} for a spherical target and for a target consisting of parallel infinite foils. The target size is plotted in units of the $\alpha\mu$ range ℓ .

Fig. 4. The muon loss probability for fusion cycles followed by muon decay in a laminated target consisting of $\Phi=1$ deuterium-tritium mixture and gold foils of interspacing r . The infinite target muon loss probability is assumed to be $(1 - R_o)\omega_s^\circ + \omega_h = 0.5\%$. Results are given for three different values of ω_h . The shaded area between two lines of equal ω_h corresponds to different choices of diffusion range of the muonic atomic or molecular states that constitutes the side channel. The maximum diffusion range considered is equal to the diffusion range of ground-state μd -atoms.

MUON LOSSES BY DECAY AND ABSORPTION

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.