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Slow and monoenergetic $(^3He\mu^-)^+$ beam production and novel applications

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Based upon the recent discovery at UT MSL/KEK, a new idea is proposed for producing a slow and monoenergetic (3.2 keV) $(^3He\mu^-)^+$ ion beam by using particle decay of the $(d^3He\mu)$ muon molecule formed during the $(d\mu)$ to ^3He transfer reaction. The proposed intense $(^3He\mu)$ beam as well as the less intense $(^4He\mu)$ beam will open up way to various new types of important μCF experiments.

So far, several proposals have been made for the possible slow beam sources of negative muons, μ^-. Recently, a realization of a slow μ^- beam has been pointed out by utilizing the successive μ^- liberation phenomena in muon catalyzed $(dt\mu)$ fusion [1,2]. The successive (above 100 times) liberation of slow (around 10 keV) μ^- after fusion reaction in the $(dt\mu)$ molecule is used to produce slow μ^- from the surface of a thin solid D–T layer.

In the recent experiments conducted by the UT-MSL and RIKEN group at UT-MSL/KEK, the following remarkable observations have been made for the μ^- transfer phenomena in liquid D_2 with ^3He and ^4He impurities [3]: 1) When negative muons are injected into high density (liquid or solid) D_2 with a low concentration (up to 500 ppm) of He impurities, all the μ^- form muonic $(d\mu)$ atoms and reach the ground state of $(d\mu)$; 2) Then, the transfer reaction of the μ^- from d to He, $(d\mu) + He \rightarrow (He\mu) + d$, takes place through the formation of the $(dHe\mu)$ muon molecule in the $(dHe\mu)_{2p\sigma}$ state (see fig. 1); 3) The $(dHe\mu)_{2p\sigma}$ has the following processes as possible decay modes: a) a radiative transition to the unbound ground state, $(dHe\mu)_{2p\sigma} \rightarrow \gamma(6.8\text{ keV}) + (He\mu)_{1s} + d$ and b) energetic emission of $(He\mu)_{1s}$ particles, where the $(d^4He\mu)_{2p\sigma}$ decays mainly (more than 60%) through the radiative transition (process (a)) and the $(d^3He\mu)_{2p\sigma}$ decays mainly (more than 80%) through the particle emission (process (b)).

As for the particle emission decay of $(d^3He\mu)$, it can be expected that the ionic particle of $(^3He\mu)^+$ is emitted at the unique energy of 3.2 keV. Once the $(d^3He\mu)$ molecule is formed, almost all the μ^- is emitted in the form of energetic $(^3He\mu)^+$ ion.

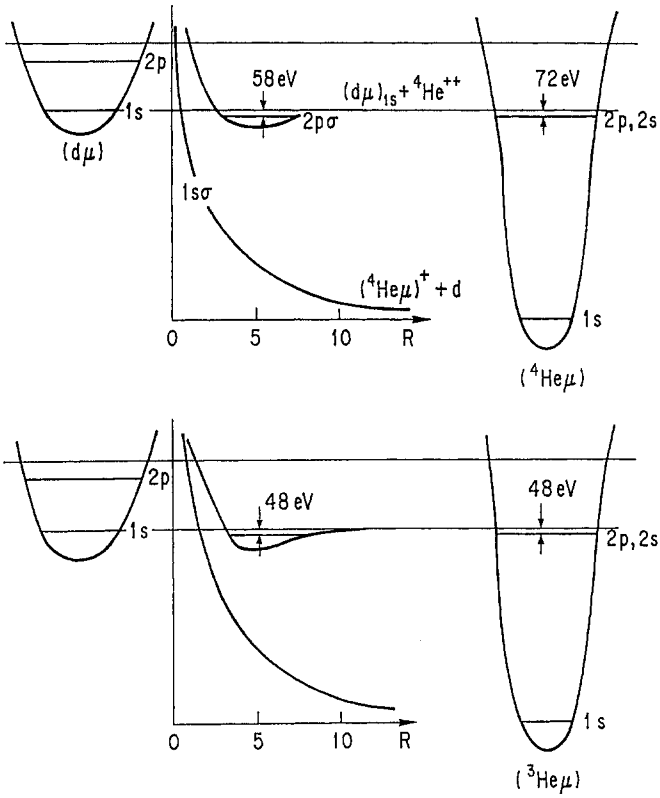

Fig. 1. Schematic diagram of energy levels of (dμ), (dHeμ) and (Heμ) for ^4He (upper) and for ^3He (lower).

Thus, the following scheme can be considered as for the method of producing a slow $(^3He\mu)^+$ particle beam. Suppose a solid layer of H_2 with 1000 ppm D_2 is formed on the cold plate (~ 3 K) with a thickness of around 1 mm. Then, a thin layer-coating of ^3He is made on the surface of solid $H_2(D_2)$. The injected μ^- of MeV energy is almost fully stopped in the thick solid $(H_2(D_2)$ layer. There, because of the well-known Ramsauer resonance effect, the (dμ) of 2 eV is produced with a long diffusion length (up to 1 mm) without any scattering from H [4,5]. Thus, a half of (dμ) reaches the layer of ^3He. Then, almost all of these (dμ) atoms form the $(d^3He\mu)$ molecules and subsequently the 3.2 keV $(^3He\mu)$ is emitted (see fig. 2).

A detailed estimation of the conversion efficiency ϵ_c from MeV μ^- to 3.2 keV $(^3He\mu)^+$ can be done by decomposing it into the following factors: a stopping rate of MeV μ^- into 1 mm thick $H_2(D_2)$, ϵ_{stop}; releasing of 2 eV (dμ) towards ^3He layer, ϵ_{rel}; thermalization rate of (dμ) inside the ^3He layer, ϵ_{th}; formation rate of the muon molecule of $(d^3He\mu)$, $\epsilon_{dHe\mu}$; emission rate of ^3He from ^3He layer, ϵ_{em} $(\epsilon_c = \epsilon_{stop}\epsilon_{rel}\epsilon_{th}\epsilon_{dHe\mu}\epsilon_{em})$.

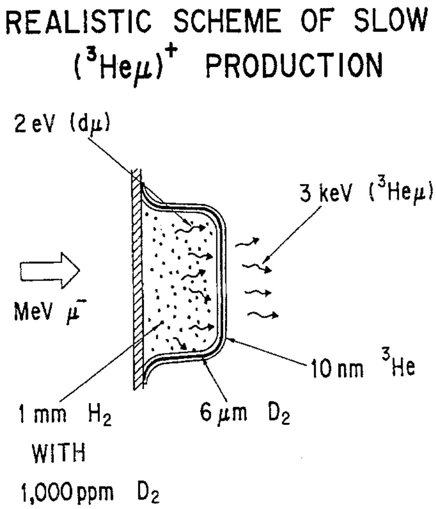

Fig. 2. Schematic picture for the target arrangement for slow $(^3He\mu^-)$ production from a ^3He coated H_2/D_2 target.

According to the experimental observations [4], $\epsilon_{stop}\,\epsilon_{rel}$ is expected to be around 0.1. As for the other factors, it should be noted that a few eV (dμ) cannot be effectively used for (d^{3}Heμ) formation for the thin ^{3}He layer whose thickness should be anyway comparable to the range of 3.2 keV (^{3}Heμ) ($\sim$ 8 nm). Therefore, we propose to place an intermediate layer of D_2 between $H_2(D_2)$ and ^{3}He in order to thermalize 2 eV (dμ) before entering the thin layer of (^{3}Heμ). After some realistic calculations [6], we found that a 6 μm D_2 layer is suitable to produce thermalized (dμ) with an efficiency of 80% ($\epsilon_{th} = 0.8$). The value of 6 μm for the D_2 layer to thermalize a few eV (dμ) is consistent with recent observations at TRIUMF [7]. Thus, by using already known values of $\epsilon_{dHe\mu}\epsilon_{em} \sim 0.80$ for 8 nm thin ^{3}He, we obtain $\epsilon_c \sim 0.06$.

The formation of a thin ^{3}He layer on solid H_2/D_2 surface could be relatively easily done by the presently available experimental methods developed for well-known low temperature physics experiments [8]; a thin ^{3}He layer can be formed with the help of Van der Waals force at relatively high temperature (a few K).

The proposed method of slow beam production might be the most efficient way among the μ^- associated particles next to the pure μ^- and the neutral muonic hydrogen. Since the $(^3He\mu)^+$ beam can be easily accelerated or deceleated, it can be stopped in a single atomic layer of material surface and/or can be focussed onto a small spot of μm order.

The possible applications as well as future extensions of the slow monoenergetic (^{3}Heμ) beam are listed in the following:

(1) Studies of the high energy resonance states in (d^{3}Heμ) molecules [9] by adjusting the (^{3}Heμ) energy and a possible application to the new muon catalyzed fusion phenomena.

(2) Direct measurement of the regeneration process by controlling the energy of $(^3He\mu)^+$. Along this line, although intensity is substantially weaker, the $(^4He\mu)^+$ beam can also be used.

(3) Production of the highly polarized $(^3He\mu^-)$ state with polarized ^3He by the repolarization method [10] and a possible application to the new μSR experiments.

(4) Detachment of μ^- from $(^3He\mu^-)$ could be realized by an interaction of the accelerated $(^3He\mu^-)$ up to several hundreds keV with, e.g., a thin foil.

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