Muonic molecule formation in muon-catalyzed fusion

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Abstract. A negative muon induces nuclear-fusion reactions between hydrogen isotopes. In this reaction, a muon plays a role of a catalyst, i.e. muon injection causes a chain reaction of nuclear fusions in hydrogen system. This phenomenon is called muon catalyzed fusion or $\mu$CF for short. A fusion reaction itself is dominated by nuclear force in the energy range of mega-electron-volt, however $\mu$CF reaction is affected by much-low-energy phenomena like temperature and density in the range of milli-electron-volt. This is due to the muonic molecule formation through which a fusion reaction occurs. Therefore, $\mu$CF has been an attractive subject for atomic physics as well as nuclear physics.

1. Introduction

A negative muon stopped in a deuterium and tritium (D-T) mixture induces $dt$-fusion through the formation of $dt\mu$ molecule: $d + t + \mu^- \rightarrow dt\mu \rightarrow \alpha + n + \mu^- + Q(17.59\ MeV)$. After this reaction, the muon is relieved and induces a subsequent fusion reaction. As shown in Fig. 1, this chain reaction ($\mu$CF cycle) repeats until the muon is lost from the cycle by either muon decay or muon capture to a higher-Z particle, like the fusion-product ($\alpha$).

It is widely accepted that a $dt\mu$ molecule can be regarded as being resonantly formed in a two-body collision between $t\mu$ and $D_2$: $t\mu + D_2 \rightarrow [(dt\mu)dec] [1]$. In this reaction, the collisional energy and the binding energy of $dt\mu$ molecule are absorbed by the rotational and vibrational energy of the $[(dt\mu)dec]$ complex, as shown in Fig. 2. This resonant formation mechanism has succeeded to explain a high muon cycling rate, which is predominantly determined by the $dt\mu$ formation rate. It was natural that a theoretical calculation based on this mechanism [2] predicted the $dt\mu$ formation rate to decrease steeply with decreasing temperature below 100 K, at which the collisional energy did not reach the lowest resonance level. However, this was not consistent with the experimental results [3, 4, 5], and even in liquid and solid D-T mixture, high fusion rate was observed.

There is another discrepancy between the resonant $dt\mu$ formation mechanism and the experimental result. Let us consider the density dependence of the muon cycling rate ($\lambda_c$), which is normalized by the target density in order to remove any trivial density dependence. Because the conventional resonant $dt\mu$-formation mechanism has been based on a two-body
collision between $t\mu$ and $D_2$, $\lambda_c$ is expected not to depend on the density. However, $\lambda_c$ shows obvious density dependence [4].

Several theoretical approaches [6, 7, 8] have been provided to solve these problems. The idea of a three-body collision during $dt\mu$ formation was proposed by Menshikov et al. [6]. They hypothesized molecular formation in a three-body system, $t\mu + D_2 + D_2'$, in which the resonant molecular formation is enhanced compared with that in a two-body system by the third particle, $D_2'$, which takes away the excess energy of molecular formation like Feschbach-resonance. This idea allows molecular formation below the above-mentioned threshold energy, and thus can
explain the temperature dependence. The contribution of the third particle may also explain the density dependence. Although qualitative explanation was provided, theoretical studies based on the three-body (many-body) effect predict different tendency of molecular formation rate in low temperature from each other.

This study aims to unveil the mystery in muonic molecule formation by performing a comprehensive survey of $\mu$CF in solid and liquid.

2. $\mu$CF experiment at the RIKEN-RAL Muon Facility

A systematic study of $\mu$CF in liquid and solid D-T mixtures was performed at the RIKEN-RAL Muon Facility [9]. An advanced tritium gas-handling system, which had an in-situ $^3$He-removal capability with a palladium filter [10], was applied to prepare a D-T mixture gas with an intended tritium concentration from 20% to 70%. By controlling the cryogenic system, the target cell was adjusted to an intended temperature from 5 to 16 K. By synchronized detection with the intense pulsed muon beam [9], X-rays associated with the muon-to-$\alpha$-sticking phenomenon were clearly observed [5, 11]. Fusion neutrons were also observed [12].

![Figure 3. The experimental setup for $\mu$CF at the RIKEN-RAL Muon Facility.](image)

The $\mu$CF cycle is characterized by the muon cycling rate ($\lambda_c$) and the total muon loss probability per cycle ($W$). These two parameters are associated with quantities determined by neutron detection, i.e., the neutron yield ($Y_n$) and the neutron disappearance rate ($\lambda_n$):

$$Y_n = \int \phi \lambda_c \exp(-\lambda_n t) dt = \frac{\phi \lambda_c}{\lambda_n},$$

$$\lambda_n = \lambda_0 + W \phi \lambda_c,$$

where $\phi$ is the atomic-number density of the D-T mixture, and $\lambda_0$ is the muon decay rate ($0.455 \times 10^6$ s$^{-1}$). As shown in the above equations, $\lambda_c$ has already been normalized by the target density in order to remove any trivial density dependence. Figure 4 shows a typical analysis result. As shown in this figure, with decreasing temperature, unexpected decrease in $\lambda_c$ and increase in $W$ were observed. The former change is interpreted to be caused by
the temperature dependence in the $dt\mu$ formation process. The most probable origin of the latter change is the temperature dependence in the muon reactivation process after muon-to-$\alpha$ sticking. The $dt\mu$ formation rate can be derived as shown in Fig. 5. A theoretical calculation which took into account a three-body effect phenomenologically predicted the enhancement in $dt\mu$ formation [13] and reproduced the present result by the transition energy from $t\mu$ to $dt\mu$ shifting from 0.601 eV to 0.596 eV. The temperature dependence of the $dt\mu$ formation rate is able to be understood by multi-body effect, i.e. Feshbach resonance mechanism, and affect $\lambda_c$ to decrease with decreasing temperature. On the other hand the increase in $W$, which is predominantly determined by the muon-to-$\alpha$ sticking probability $\omega^{eff}_s$, is still open question.

The muon sticking process is divided into two processes, initial sticking and a subsequent reactivation process: $\omega^{eff}_s = (1 - R)\omega_0^s$, where $R$ is the reactivation probability. Because the initial sticking denoted by $\omega_0^s$ is a process immediately after a nuclear reaction, it is unnatural that the surrounding molecules affects this process. Thus, the temperature dependence in $\omega^{eff}_s$ is implied that the reactivation process depends on the temperature. Concerning the $\alpha$-sticking process, we obtained other information by X-ray detection. The $K_\alpha$ X-ray yield from muon-to-$\alpha$ sticking was observed to be constant with the temperature. Although both $R$ and the sticking X-ray yield describe the sticking process, only $R$ shows a temperature dependence. This difference is understandable by taking into account the fact that almost all of the sticking X-rays which have a Doppler width corresponding to the fusion Q-value are emitted before the thermalization of an $(\alpha\mu)^+$ ion [5]. Namely, the temperature dependence in $R$ can be explained by an assumption that the reactivation after thermalization or during thermalization depends on the temperature. Although the reactivation has been interpreted to occur in an high energy collision between an $(\alpha\mu)^+$ ion and surrounding hydrogen molecules, the present study observed the first evidence of the reactivation after thermalization, which is not negligible in comparison with that before thermalization.

**Figure 4.** A typical result of the temperature dependence of (a) $\lambda_c$, (b) $W$, and (c) the ratio of the muon-to-$\alpha$-sticking X-ray yield to the fusion neutron yield at the tritium concentration of 40%.

**Figure 5.** The temperature dependence of the molecular formation rate. The present work and theoretical calculations [2, 13] are shown. In the upper solid curve, the transition energy from $t\mu$ to $dt\mu$ is assumed to be 0.596 eV, while the lower is 0.601 eV.
3. Conclusion
The temperature-dependent phenomena of $\mu$CF were clearly observed in solid D-T mixtures. This shows the existence of multi-body effect in $dt\mu$ formation mechanism and also in the muon reactivation process after muon sticking to a fusion product of an $\alpha$ particle. Applying the nuclear-fusion reaction to a research probe, the present work has brought the mystery of $\mu$CF concerning the atomic physics in relief. A $\mu$CF study of ortho and para enriched deuterium system also shows an evidence of Feshbach resonance in $dd\mu$ formation [14].

In addition to the atomic physics, $\mu$CF study produces fruitful results in nuclear physics [10] and condensed matter physics [16]. High intensity pulsed muon beam is a key technique for the present work, and thus J-PARC Muon Facility is expected to promote this interdisciplinary research.

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