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# Status of J-PARC E73 experiment: first direct Hypertriton lifetime measurement with $^{3}$He($K^{-}$, $\pi^{0}$)$^{3}_{\Lambda}$H reaction

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In the last decade, heavy-ion based experiments (HypHI, STAR and ALICE$^{i}$) announced surprisingly short lifetime for $^{3}_{\Lambda}$H mesonic weak decay (MWD), which is difficult to interpret given the fact that $^{3}_{\Lambda}$H is a very loosely bound system. It will be very interesting to study this issue with a different experimental approach. We propose a direct measurement for $^{3}_{\Lambda}$H hypernucleus MWD lifetime with $\sim$10% precision as J-PARC E73 experiment; $^{4}_{\Lambda}$H hypernucleus lifetime will also be measured as a feasibility test for our experimental approach. In this proceeding, we will introduce the experimental method and the current status of E73 experiment.

*Keywords:* Hypertriton; lifetime puzzle; fast calorimeter.

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## 1. Introduction

The $^{3}_{\Lambda}$H lifetime puzzle stands for an unexpected large discrepancy between the weak decay lifetime of $\Lambda$ hyperon and $^{3}_{\Lambda}$H. As the lightest bound hypernucleus, $^{3}_{\Lambda}$H is characterized by its small binding energy ($B_{\Lambda}$=130$\pm$50 keV [1]). Consequently, the $\Lambda$ hyperon is well separated by $\sim$10 fm from the deuteron core inside the $^{3}_{\Lambda}$H. It is natural to expect that the weak decay lifetime of $^{3}_{\Lambda}$H is similar to that of $\Lambda$ hyperon ($\tau \sim 263$ ps) because of little effects from the deuteron core due to large separation of the wave function. However, in the period $2013-2018$, several heavy-ion based experiments reported much shorter $^{3}_{\Lambda}$H lifetime than the $\Lambda$ hyperon by up to $\sim$30% (STAR [2], ALICE [3] and HypHI [4]). It is even more puzzling that, very recently, both STAR and ALICE collaborations updated their measurements for $^{3}_{\Lambda}$H lifetime, which becomes similar to the free $\Lambda$ hyperon one [5, 6]. This situation is summarized in Table I. Here we have to point out that the $^{3}_{\Lambda}$H lifetime puzzle can not be solved by heavy-ion based approach itself because of a possible mixture between spin 1/2 and 3/2 states during production in heavy ion collisions. So that the $^{3}_{\Lambda}$H data sample from heavy-ion based production is distorted from the true lifetime of $^{3}_{\Lambda}$H ground state. We propose to solve this problem by selectively populate spin 1/2 ground state with the J-PARC E73 experiment.$^{ii}$

TABLE I. Summary of recent measurements on ${}^{3}_{\Lambda}$H lifetime.

| Collaboration | Experimental method | ${}^{3}_{\Lambda}$H lifetime [ps] | Release date |
|---|---|---|---|
| HypHI | fixed target | $183^{+42}_{-32}$(stat.)±37(syst.) | 2013 [4] |
| STAR | Au collider | $142^{+24}_{-21}$(stat.)±29(syst.) | 2018 [2] |
| | | 221±15(stat.)±19(syst.) | 2021 [6] |
| ALICE | Pb collider | $181^{+54}_{-39}$(stat.)±33(syst.) | 2016 [3] |
| | | $242^{+34}_{-38}$(stat.)±17(syst.) | 2019 [5] |

## 2. J-PARC E73 experiment principle

As a general property for the hypernucleus production process, $\Lambda$ hyperon with small recoiling momentum has a large probability to form a hypernuclear bound state. This argument is particularly true for $s$-$shell$ hypernucleus because there is only one bound state for $\Lambda$ hyperon in $s$-$orbit$ and any $\Delta p \geq 200$ MeV/$c$ reaction will cause $\Delta l = 1$ transition and break the bound state. The $\Lambda$ hyperon production kinematics with ($K^-$, $\pi^0$) reaction is illustrated in Fig. 1, from which it is clear that the forward scattered $\pi^0$ events are favorable for the hypernucleus production. Another important merit of choosing the kinematics with small $\Lambda$ recoiling momentum is the selectivity for the spin non-flip ground state (J=1/2) ${}^{3}_{\Lambda}$H production, which is not self-evident for the heavy-ion based experiments.

It is therefore necessary to find a method to effectively select the forward boosted $\pi^0$ events from the large hadronic background. To fulfill this request, we adopt an innovative approach to select the forward $\pi^0$ by tagging the high energy $\gamma$ rays decayed from the $\pi^0$ meson. The working principle is demonstrated in Fig. 2, the fast $\pi^0$ at the forward scattering angle boosts the decayed $\gamma$ rays more forwardly than the slow ones. So that by tagging the high energy $\gamma$ rays, we can effectively select the forward $\pi^0$ events with very good efficiency.

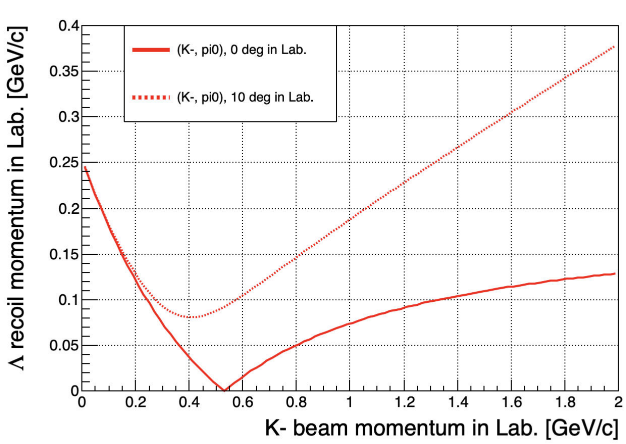


FIGURE 1. $\Lambda$ hyperon production kinematics.

As illustrated in Fig. 3, the $\gamma$ ray energy detector, the calorimeter, has to be placed in the very forward direction overlapping with the trajectory of the meson beam. Thus the calorimeter has to be very fast and radiation hard. An almost pure Cherenkov radiator, $PbF_2$ crystal was chosen to construct the forward calorimeter to guarantee a good separation between high-energy gamma ray and hadrons such as charged kaon and pion. Typical signals from $PbF_2$ crystal have ~20 ns width, which makes the detector dead time very short. Another merit to use $PbF_2$ crystal is for its radiation hardness. For example, even if exposed to 1MHz pion with 1 GeV/$c$ momentum for one month, there is no essential degradation for the Cherenkov light yield. A reasonably good energy resolution of $\sim 5\%$ at 1GeV/c is helpful to suppress background channels such as quasi-free $\Lambda$ hyperon produc-

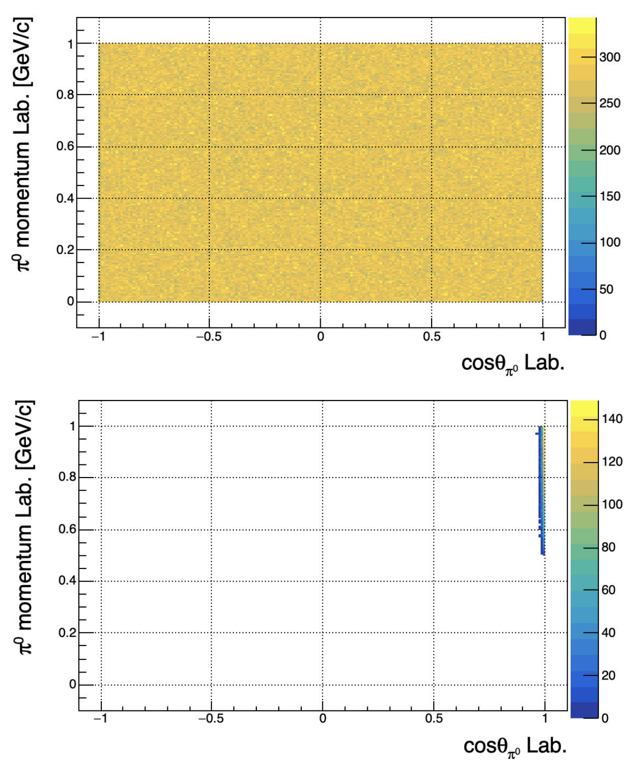


FIGURE 2. Forward $\pi^0$ selection by tagging high energy $\gamma$ rays. Upper: uniformly distributed $\pi^0$ events in Lab. frame; lower: forward $\pi^0$ events after selecting the high energy $\gamma$ with $E_\gamma$ ≥500 MeV.

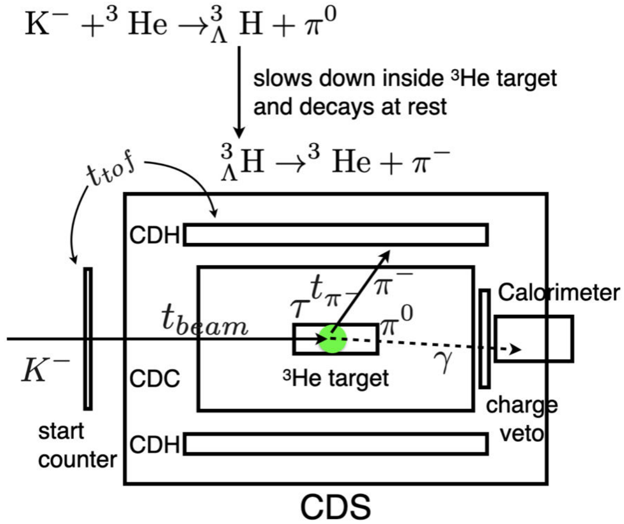


FIGURE 3. Schematic setup for J-PARC E73 experiment.

tion. All these together make the $PbF_2$ crystal an ideal candidate for our forward calorimeter. For the details of calorimeter design and performance, please refer to our recent work [7].

The schematic setup of E73 experiment is shown in Fig. 3. The $PbF_2$ calorimeter is installed in the very forward region to tag fast $\pi^0$ meson emitted at $\sim$0 degree, which corresponds to small recoiling momentum of $\Lambda$ hyperon. Such a selection will improve the ratio between ${}^3_\Lambda$H and quasi-free $\Lambda$ and $\Sigma$ background. A Cylindrical Detector System (CDS) used in J-PARC E15/E31 experiment is employed to track the $\pi^-$ following the ${}^3_\Lambda$H hypernucleus weak decay [8]. The $\pi^-$ decayed from ${}^3_\Lambda\text{H}\rightarrow{}^3\text{He}+\pi^-$ has a fixed momentum of $\sim$ 113 MeV/c, which can be used to extract the signal from the quasi-free $\Lambda/\Sigma$ in-flight decay background.

As illustrated in Fig. 3, the relation between ${}^3_\Lambda$H decay time and experimental observable is

$$t_{\text{tof}} = t_{\text{beam}} + t_{\pi^-} + \tau, \tag{1}$$

where $t_{tof}$ is the TOF between the start counter and the CDH counter, $t_{beam}$ is the $K^-$ TOF between start counter and reaction vertex, $t_{\pi^-}$ is the TOF of $\pi^-$ between decay vertex and CDH and $\tau$ is the ${}^3_\Lambda$H decay time to be determined by the experiment. The value of $t_{beam}$ and $t_{\pi^-}$ can be calculated by CDS tracking. The $\tau$ obtained this way is not the $exact$ lifetime of ${}^3_\Lambda$H yet but the lifetime convoluted with CDS time resolution, which can be written as:

$$f(t) = \int_{-\infty}^{+\infty} e^{-(t-u)/\tau} R(u) du, \tag{2}$$

where $R(u)$ is the response function due to limited time resolution. The expression of $R(u)$ can experimentally obtained by using the prompt ($\pi^-$, $\pi^-$) hadronic reaction, where the $u$ stands for the time variable of the response function. This relation is used, in turn, to fit the $\pi^-$ time distribution and derive the ${}^3_\Lambda$H lifetime. This capability to derive the ${}^3_\Lambda$H lifetime in time domain forms the essential idea of *direct measurement* in comparison with heavy-ion based experiments, where the decay length is used to fit the hypertriton lifetime.

## 3. Current status and outlook

Our experimental proposal has been approved as J-PARC E73 experiment in 2020. As suggested by the J-PARC Physics Advisory Committee, our E73 experiment will be carried out in three stages: the first stage is to prove the feasibility of the experimental method; the second stage is to measure the production cross section of hypertriton with charge exchange reaction; the third stage is to accumulate enough statistics to derive the hypertriton lifetime. As of May 2021, we have successfully completed the first two stages.

As the first stage, feasibility study has been carried out in May 2020 (J-PARC T77 experiment) with liquid ${}^4$He target because of higher signal to noise ratio than ${}^3$He, which is ideal for a short pilot experiment. With 3 days of beam time at 50 kW beam power, we were able to collect a world record of $\sim$1k ${}^4_\Lambda$H events with 2 times higher statistics and $\sim$10 times better signal to noise ratio than the previous KEK experiment [9]. As the second stage, the hypertriton production cross section measurement has been completed in May 2021. We have successfully observed ${}^3_\Lambda$H from both 2-body and 3-body decay of hypertriton ground state. This observation provides the first direct determination for the ground state spin of hypertriton as 1/2. Based on the previous results and experience, we are ready for the final data taking in 2023.

$i$. Recently, STAR and ALICE updated their results, which becomes close to the free $\Lambda$ lifetime. See text for details.

$ii$. There are two possible effects for the ${}^3_\Lambda$H lifetime measurement from the mixture of spin 1/2 and 3/2 states: the 3/2 excited state may have a different lifetime from 1/2 ground state especially for the two-body/three-body decay branching ratio because of the angular momentum conservation; the $M1(\frac{3}{2} \rightarrow \frac{1}{2})$ transition ($E_\gamma \sim 100$ keV, if 3/2 state is bound) has a lifetime comparable with its weak decay and results in a chained decay which distorts the lifetime measurement.

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