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Hypertriton Lifetime Puzzle and Its Perspective

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Abstract: Recent heavy ion experiments (HypHI, STAR) announced surprisingly short lifetime for $^{3}_{\Lambda}\mathrm{H}$ mesonic weak decay (MWD), which is difficult to interpret given the fact that $^{3}_{\Lambda}\mathrm{H}$ is a very loosely bound system. This intriguing issue is known as hypertriton lifetime puzzle. In order to test the lifetime of the hypertriton with different experimental methods, we propose to use the K^- beam of J-PARC to measure the lifetime of the hypertriton through the reaction channel of $\mathrm{K}^- + {}^{3}\mathrm{He} \rightarrow {}^{3}_{\Lambda}\mathrm{H} + \pi^0$. In this article, we will summarize the situation and introduce some recent activities aiming at solving this puzzle. Our method will not suffer from the track reconstruction efficiency as the heavy ion based experiments; thus provide an important test for the hypertriton lifetime puzzle with comparable precision.

Key words: Hypernucleus; hypertriton lifetime; Cherenkov calorimeter

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1 Introduction

Hypertriton ($^{3}_{\Lambda}\mathrm{H}$) is the lightest Hypernucleus system consisting one neutron, one proton and one Λ hyperon. Similar to the role played by deuteron in Nuclear Physics, hypertriton is expected to provide important knowledge for Hyperon-Nucleon (YN) interaction from its binding energy, ground state spin and so on. In addition, hypertriton can decay with flavor changing weak decay, which is very sensitive to the nucleon wave function and redcan serve as a good probe for the internal structure of the target hypernucleus. There are two modes of weak decay for Hypernucleus: mesonic and non-mesonic decay. The mesonic decay occurs by emitting one pion similar to the decay of freeΛ hyperon; for non-mesonic decay, there is no real pion emitted and this part of energy are shared between decay products such as neutron and other fragments. Non-mesonic weak decay usually happens in heavier hypernucleus and light hypernucleus decays via mesonic weak decay predominantly.

For any unstable system decays with multiple decay channels, the derived lifetime from each decay channel is the same as total lifetime. The only difference comes from the branching ratio of each decay channel, which determines its contribution to the total lifetime. For instance, the famous $\theta-\tau$ puzzle[1], which inspired the idea of parity violation, has both 2-π and 3-π decay channels with the same lifetime but different branching ratio. The lifetime of $^{4}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{He}$ has been measured as 194^{+24}_{-26} ps and (256 ± 27) ps, respectively[2]. The difference of lifetime between $^{4}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{He}$ can be explained by observing the energy release together with $\Delta I{=}1/2$ rule of Λ hyperon decay. For both $^{4}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{He}$, the most stable decay product is $^{4}\mathrm{He}$ with similar energy release. However, the $\Delta I{=}1/2$ rule requests that the branching ratio of $\Lambda\rightarrow \mathrm{n}+\pi^0/\Lambda\rightarrow \mathrm{p}+\pi^-=1/2$. For $^{4}_{\Lambda}\mathrm{He}$, the π^0 decay channel is suppressed and the lifetime is longer than $^{4}_{\Lambda}\mathrm{H}$, which can decay with π^- channel into stable $^{4}\mathrm{He}$. It is this effect that facilitates the decay of $^{4}_{\Lambda}\mathrm{H}$. As a result, $^{4}_{\Lambda}\mathrm{H}$ has a shorter lifetime than Λ hyperon and the lifetime of $^{4}_{\Lambda}\mathrm{He}$ is predominantly determined by the decay of free Λ.

On the other hand, for the case of hypertriton, besides phase space and $\Delta I{=}1/2$ rule, the wave func-

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tion distribution also contributes to its lifetime. This is because of the uniquely small binding energy of $^{3}_{\Lambda}\mathrm{H}$ system compared to A=4 hypernucleus system [$B_{^{3}_{\Lambda}\mathrm{H}}$=(0.13±0.05) MeV[3], $B_{^{4}_{\Lambda}\mathrm{He}}$=(2.39±0.03) MeV[4] and $B_{^{4}_{\Lambda}\mathrm{H}}$=(2.12±0.01) MeV[5]]. As one can easily estimate by assuming a harmonic type potential inside $^{3}_{\Lambda}\mathrm{H}$, the average distance between Λ hyperon and deuteron core is in the order of 10 fm, which has been confirmed by high precision few-body calculation[6]. Such a wide spread system will suppress the decay rate because of the small probability for the formation of $^{3}\mathrm{He}$ wave function. Thus $^{3}_{\Lambda}\mathrm{H}$ is expected to possess a similar lifetime as free Λ hyperon [τ =(263.2±2.0) ps][7].

2 Hypertriton lifetime measurement

The early results for the hypertriton lifetime are obtained from nuclear emulsion and Helium bubble chamber experiments. The hypertriton can be populated as the hyper fragments in nuclear emulsion or directly generated as $\mathrm{K}^{-}+{}^{4}\mathrm{He} \rightarrow {}^{3}_{\Lambda}\mathrm{H}+\mathrm{p}+\pi^{-}$ in Helium bubble chamber. All charged particle tracks from reaction and decay were recorded in emulsion or bubble chamber photograph. Events were reconstructed based on its energy deposit and vertex, which can be used to derive the weak decay lifetime. The results are summarized in Table 1. Except one early result with large error bar[8] and one emulsion data[11], the majority of the measurement gives $^{3}_{\Lambda}\mathrm{H}$ lifetime close to the Λ hyperon.

Table 1 Summary of early measurements on $^{3}_{\Lambda}\mathrm{H}$ lifetime.

Experimental method	$^{3}_{\Lambda}\mathrm{H}$ lifetime /ps	Statistics	Released date
Nuclear emulsion	90^{+220}_{-40}(stat.)	4	1964[8]
Helium bubble chamber	232^{+45}_{-34}(stat.)	52	1968[9]
Nuclear emulsion	285^{+127}_{-105}(stat.)	54	1969[10]
Nuclear emulsion	128^{+35}_{-26}(stat.)	156	1970[11]
Helium bubble chamber	264^{+84}_{-52}(stat.)	27	1970[12]
Helium bubble chamber	246^{+62}_{-41}(stat.)	40	1973[13]

However, the situation has been changed recently. Two heavy ion experiments(STAR[14–15], HypHI[16]) found surprisingly short lifetime for $^{3}_{\Lambda}\mathrm{H}$ in their measurements. Another experiment based on LHC (ALICE[17–18]) previously reported a similar short lifetime[17] but recently updated their result[18], which becomes closer to the theoretical estimation. These new results are summarized in Table 2. According to the results from STAR and HypHI, $^{3}_{\Lambda}\mathrm{H}$ has a lifetime ∼ 30% shorter than Λ hyperon, which is in conflict to the argument mentioned above. One theoretical investigation searching for possible explanation propose the effect of surrounding nucleon facilitate the decay of $^{3}_{\Lambda}\mathrm{H}$[19]. However, more direct evidence is needed to verify the existence of such effect. In a recent calculation[20], A. Gal and H. Garcilazo could reproduce the hypertriton lifetime as ∼0.8 of τ_{Λ} [$\tau_{^{3}_{\Lambda}\mathrm{H}}$ ∼(215±5) ps]. According to them, the attractive pion final state interaction facilitates the decay of hypertriton, which results in a shorter lifetime. Another progress comes from the binding energy measurement of hypertriton by STAR collaboration[21]. Instead of ∼0.13 MeV, STAR's new result gives B_{Λ}∼0.4 MeV. This binding energy suggests a larger overlap between Λ hyperon and deuteron core, which helps the decay of hypertriton system. But a larger binding energy also reduces the energy release during hypertriton decay, which, in turn, reduces the decay probability. Given such a complicated situation, new experimental investigation, especially independent approach from heavy ion experiments, is highly demanded to pin down the puzzle.

Table 2 Summary of recent measurements on $^{3}_{\Lambda}\mathrm{H}$ lifetime.

Experimental method	$^{3}_{\Lambda}\mathrm{H}$ lifetime/ps	Statistics	Released date
Au collider (STAR)	142^{+24}_{-21}(stat.)±29(syst.)	∼577	2018
Pb collider (ALICE)	181^{+54}_{-39}(stat.)±33(syst.)	∼55	2016
Pb collider (ALICE)	242^{+34}_{-38}(stat.)±17(syst.)	∼200	2019
Fixed target (HypHI)	183^{+42}_{-32}(stat.)±37(syst.)	∼154	2013

One should notice that a common data analysis method used in heavy ion experiment was to reconstruct both reaction and decay vertex of $^{3}_{\Lambda}\mathrm{H}$ in order to derive in-flight decay length L. The $^{3}_{\Lambda}\mathrm{H}$ lifetime can be expressed into in-flight decay length as $\tau = L/\beta\gamma c$, where τ is the measured lifetime in hypertriton rest frame, L is the reconstructed decay length at Laboratory frame, β and γ are the velocity and Lorentz boost factor for the current event. It is natural to perform a direct lifetime measurement for $^{3}_{\Lambda}\mathrm{H}$ lifetime as a complementary method to heavy ion experiment.

3 Future experiments

Three experiments aiming to directly measure $^{3}_{\Lambda}\mathrm{H}$ lifetime are planned: one is to use the $\gamma+{}^{3}\mathrm{He}\rightarrow{}^{3}_{\Lambda}\mathrm{H}+\mathrm{K}^{+}$ reaction at ELPH, Tohoku University, Japan[22]; another one is to employ $\pi^{-}+{}^{3}\mathrm{He}\rightarrow{}^{3}_{\Lambda}\mathrm{H}+\mathrm{K}^{0}$ reaction at J-PARC, Japan[23]; the last one will use $\mathrm{K}^{-}+{}^{3}\mathrm{He}\rightarrow{}^{3}_{\Lambda}\mathrm{H}+\pi^{0}$ reaction at J-PARC, Japan[24]. The first two experiments are able to reconstruct the missing mass of the reaction, which allows the selection of ground state $^{3}_{\Lambda}\mathrm{H}$. The lifetime of $^{3}_{\Lambda}\mathrm{H}$ can be directly measured by detecting π^- from two-body mesonic weak decay $^{3}_{\Lambda}\mathrm{H}\to{}^{3}\mathrm{He}+\pi^-$. The last proposal will not measure the reaction missing mass but to identify the production of $^{3}_{\Lambda}\mathrm{H}$ with the mono-energetic π^- (∼114 MeV/c) emitted from $^{3}_{\Lambda}\mathrm{H}$ two-body decay. This proposal is granted a conditional test beam about one week in next Spring with liquid ^{4}He target for feasibility study and background yield estimation. One should also notice that this K$^-$(p, Λ)π^0 reaction could be used as a new method for neutron rich hypernuclei production with coincidence measurement such as γ−ray or Auger neutron spectroscopy. We will use the last proposal as an example to illustrate the method of direct lifetime measurement.

The experimental concept is shown in Fig. 1. A Cylindrical Detector System(CDS) used in J-PARC E15/E31 experiment is employed to capture the delayed π^- as a weak decay product from $^{3}_{\Lambda}\mathrm{H}$ hypernuclei[26]; a calorimeter is installed in the very forward region to tag fast π^0 meson along ∼0 degree, which corresponds to small recoil momentum of Λ hyperon. Such a selection will improve the ratio between $^{3}_{\Lambda}\mathrm{H}$, quasi-free Λ and Σ background. After taking into account $^{3}_{\Lambda}\mathrm{H}$ production cross section(12 μb), luminosity and detector acceptance, about one thousand π^- decay events from $^{3}_{\Lambda}\mathrm{H}$ can be collected during one month beam time at J-PARC K1.8BR beam line[25].

It is essential for this experiment to effectively

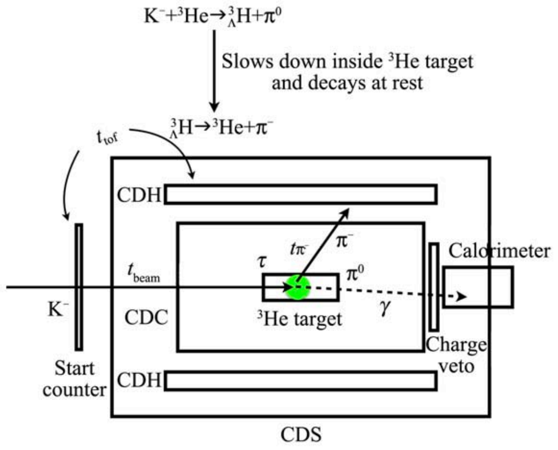

Fig. 1 (color online) Schematic view of the experimental setup; Cylindrical Detector System(CDS) is used to capture delayed π^- particle from $^{3}_{\Lambda}\mathrm{H}$ weak decay; high-energy γ rays ($E_\gamma \geqslant 600$ MeV) are tagged with PbF$_2$ calorimeter.

suppress the π^- background events to obtain a reasonable S/N ratio. The reduction of π^- counts with various event selections are shown in Fig. 2.

More specifically, the online trigger for data acquisition is: K$^-$ beam ⊗ CDH one hit ⊗ $\overline{\text{veto counter}}$ ⊗ calorimeter d$E \geqslant$600 MeV.

Offline data analysis requires that CDS has only one charged track together with fiducial volume cut. According to our simulation, most background from K$^-$ in-flight decay can be effectively suppressed and

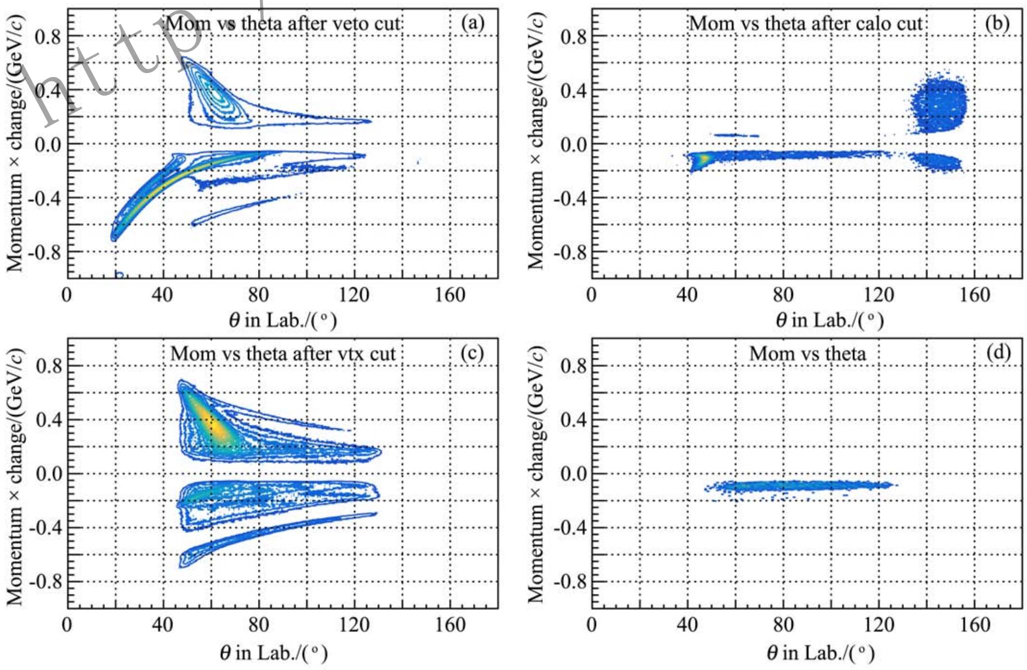

Fig. 2 (color online) Background π^- from 1.0 GeV/c K$^-$ beam bombarding ^{3}He target after various cutting conditions: (a) requesting veto counter d$E \leqslant$0.2 MeV; (b) requesting calorimeter d$E \geqslant$600 MeV; (c) requesting reaction volume within target region; (d) is obtained after applying all cutting conditions, π^- background due to in-flight decay can be effectively suppressed and only reaction induced background is left.

only reaction induced ones are left. To further study the S/N between signal π^- and reaction induced one, such as quasi-free Λ and Σ channel, we bombard the liquid Hydrogen target and scaled the results with effective luminosity[27]. Fig. 3 shows the simulation results, from which one can clearly tell the structure around 114 MeV/c is from the $^3_\Lambda$H mesonic weak decay signal. By selecting the signal region, one can obtain the total lifetime distribution as shown in Fig. 4. Background subtraction can be achieved by gating the neighbouring region in Fig. 3, which is plotted in blue in Fig. 4. Finally, the lifetime distribution of $^3_\Lambda$H mesonic weak decay is given in red by Fig. 4.

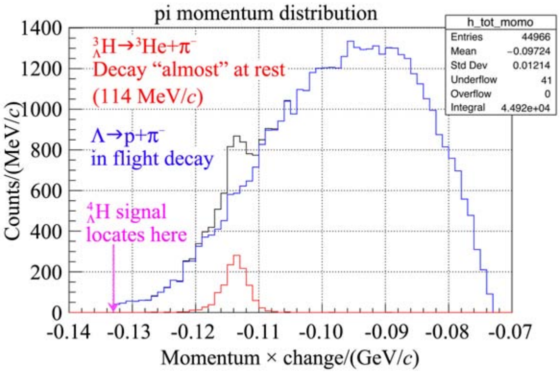

Fig. 3　(color online) π^- momentum distribution: peak in red is from $^3_\Lambda$H decay, blue curve shows π^- from other hyperon weak decay channels based on GEANT4 simulation with liquid Hydrogen target.

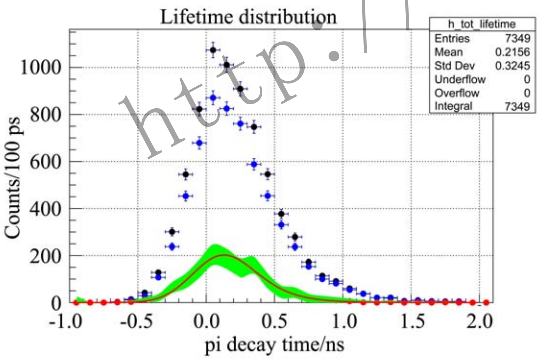

Fig. 4　(color online) Generated time distribution of π^- with S/N and statistics obtained from simulation with Hydrogen target: blue data points are background events from hyperon decay; red data points are $^3_\Lambda$H events after subtracting background distribution.

The relation of $^3_\Lambda$H lifetime and measured timing information is illustrated in Fig. 1. The experimental accessible information is $T_{\text{CDH}}-T_0$, which is composed of t_{beam}, t_{π^-} and τ_0 as

$$T_{\text{CDH}}-T_0=t_{\text{beam}}+t_{\pi^-}+\tau_0. \tag{1}$$

The value of t_{beam} and t_{π^-} can be calculated by CDS tracking*. The τ_0 is not the *exact* lifetime of $^3_\Lambda$H but the lifetime convoluted with CDS time resolution, which can be written as:

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

where $R(u)$ is the response function due to limited time resolution. By assuming $R(u)$ as a Gaussian function with $\sigma=200$ ps, which is the current CDS time resolution, the $^3_\Lambda$H lifetime can be derived by fitting the π^- time spectrum with $f(t)$. A quick fitting for Fig. 4 gives a reasonable resolution of ~20 ps (statistical) and ~20 ps (systematic).

4　Summary

In this article, we briefly described the $^3_\Lambda$H lifetime puzzle based on general consideration, early data and recent heavy ion experiment results. Some new efforts employing independent experimental method are in progressing. Our knowledge for $^3_\Lambda$H lifetime and its structure is expected to be improved in the next few years.

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*For details of vertex reconstruction and velocity derivation with CDS, please refer to Ref. [26]

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超氚核寿命之谜及其展望

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摘要： 近期，基于重离子碰撞的实验组（HypHI, STAR）发表了超氚核(hypertriton)的寿命测量结果。其结果显示，超氚核的寿命比Λ超子短～30%。由于超氚核是一个非常松散的结合态，超氚核的寿命不应远离Λ超子的寿命太多。这一难以解释的现象被称为超氚核的短寿命之谜。为了从不同的实验方法检验超氚核的寿命，我们提出利用J-PARC的K^-束流，通过$K^-+{}^3\mathrm{He}\rightarrow {}^3_\Lambda\mathrm{H}+\pi^0$的反应道来测量超氚核寿命的实验。本文将回顾测量超氚核寿命的主要结果，并介绍目前实验方面的最新进展。本合作组提出的原创性实验方案不会受到径迹重建效率的影响，能够为验证超氚核的寿命提供重要的实验数据。

关键词： 超核；超氚核寿命；切伦科夫量能器

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