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研究課題名（和文）Solve the hypertriton lifetime puzzle

研究課題名（英文）Solve the hypertriton lifetime puzzle

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研究成果の概要（和文）：我々は、ハイパートライトン(3ΛH)の詳細な寿命測定を行う目的で、全く新しい実験手法である(K-,π0)反応を用いた実験(E73)を提案している。2020年に成功した4He(K-,π0)反応からの4ΛH生成(T77実験)を受けて、次に、我々は3ΛHの生成断面積を決定することを目的としたE73パイロット実験を2021年5月に行った。得られたπ-の運動量分布において、3ΛHの2体崩壊(π-,3He)及び3体崩壊(π-,p,d)のシグナルをはっきり見ることが出来た。我々は2年後にE73本実験を行い、十分な3ΛH状態の統計を元にハイパートライトンの寿命問題解決を目指す。

研究成果の学術的意義や社会的意義
As the lightest hypernucleus, hypertriton provides the foundation for our understanding for YN interaction. With the support of this Kakenhi, our J-PARC E73 experiment essentially improved our understanding for hypertriton with our original production method (K-, pi0).

研究成果の概要（英文）：We have proposed a new experiment (J-PARC E73) to solve the hypertriton lifetime puzzle with a novel production method (K-, pi0). We demonstrated the feasibility with 4He target as J-PARC T77 experiment in 2020. We collected a world record of ~1k {\Lambda}H events with ~10 times better signal to noise ratio than previous KEK results. Our new approach may also find application for other experiments need pi0 identification such as neutron-rich hypernuclear gamma-ray spectroscopy.
As a pilot run of the E73 experiment, we have successfully measured the hypertriton production cross section in May 2021. We have clearly observed pi- from both 2-body and 3-body decay of hypertriton ground state. This observation provides the first direct determination for the hypertriton ground state spin. We are looking forward to accumulating enough statistics and solve the hypertriton lifetime puzzle in the near future with our original approach.

研究分野：Experimental Nuclear Physics

キーワード：hypertriton lifetime　Cherenkov calorimeter

１．研究開始当初の背景

Hypertriton (Λ^3H) is the lightest hypernucleus consisting one proton, one neutron and one Λ hyperon. Similar to the role played by deuteron for nuclear physics, hypertriton provides the foundation for our understanding for YN interaction. It has been known for a long time that, inside the hypertriton, the Λ hyperon is very loosely bound by a deuteron core (B_Λ=130±50keV) and well separated (~10 fm)[1]. It is thus natural to expect that the lifetime of hypertriton should be very similar to that of Λ hyperon in vacuum (τ~263ps) because of small influence from the deuteron core. However, as summarized in Table 1, several recent experiments based on heavy-ion production method (HypHI, STAR and ALICE) reported a surprisingly shorter hypertriton lifetime (up to 30%) than free Λ hyperon. *Such an unexpected short lifetime of Λ^3H posts a very challenging question to the foundation of our understanding concerning hypernucleus, which was recognized as hypertriton lifetime puzzle.*

Table 1. Summary for the recent measurements for Λ^3H lifetime

Collaboration	Experimental Method	Λ^3H lifetime [ps]	Release date
STAR [3]	Au collider	182±27	2010
HypHI [2]	Fixed target	183±37	2013
ALICE [4]	Pb collider	181±33	2015

２．研究の目的

In this project, we will try to pin down the hypertriton lifetime puzzle by establishing an independent experimental approach to measure Λ^3H lifetime directly. Different from the heavy-ion based experiments, we will employ strangeness exchange reaction, K^-+^{3}He→Λ^3H+π^0, as production channel to generate hypertriton and directly measure the time distribution of π^- emitted from Λ^3H as mesonic weak decay to obtain its lifetime. Our approach has several advantages compared with heavy-ion based experiments. First of all, the charge exchange reaction is well known for its spin non-flip feature, which enables us to measure the hypertriton ground state spin directly for the first time. (The current spin 1/2 assignment was derived from the 2-body to 3-body branching ratio with bubble chamber data, which has large theoretical ambiguity.) In other words, the contamination from the 3/2 state will be suppressed in our experiment, which cannot be excluded from the heavy-ion based experiments. In addition, our approach allows us to derive the hypertriton lifetime from a wide time range distribution and to avoid bias induced by data concentration such as the decay length distribution in the heavy-ion based experiments. In short, our experiment will be able to conclude whether there is some *"new physics"* behind the puzzling short lifetime of hypertriton or it is originated from the *"feature"* of some particular experimental approach.

３．研究の方法

Figure 1 shows the schematic experimental setup. K^- meson beam will be directed to the liquid ^{3}He target at 1GeV/c to populate hypertriton. A central tracking system (CDS) will be used to detect π^- meson decayed from Λ^3H. The CDS consists of a solenoid magnet, a central drift chamber (CDC) and a barrel of hodoscope (CDH). The details are given in [5]. Together with a charge veto counter, a forward calorimeter is used to tag the emission of high-energy gamma rays in order to select fast π^0 meson from strangeness exchange reaction. π^- emitted from Λ^3H 2-body weak decay has a mono-energetic momentum (114MeV/c), which can be used to identify the production of hypertriton. After selecting the π^- from Λ^3H mesonic weak decay, one can derive its lifetime by $\tau = t_{tof} - t_{beam} - t_\pi$ as illustrated in Figure 1.

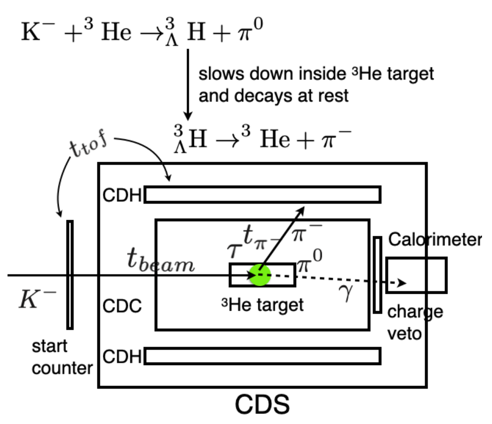

Figure 1. Schematic experimental setup

An important innovation of our experiment is to design and construct a very fast forward calorimeter to tag the forward boosted π^0 meson in order to identify the strangeness exchange reaction and enhance the signal to noise ratio of hypertriton bound state. As an almost pure Cherenkov radiator, PbF_2 crystal has been chosen to construct the forward calorimeter to guarantee a good separation between high-energy gamma ray and hadrons such as charged Kaon and pion [6]. Typical signals from PbF_2 have ~20ns 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 1GeV/c for one month, there is no essential degradation for the Cherenkov light yield [6]. A reasonably good energy resolution of ~5% is helpful to suppress background channels such as quasi-free Λ hyperon production. All these together make the PbF_2 crystal an ideal candidate for our forward calorimeter. Some important properties of PbF_2 are summarized in Table 2.

Table 2, Summary of PbF2 crystal property

Crystal	Radiation length	Moliere radius	Density	Resolution	Cost
PbF_2	0.93 cm	2.22 cm	7.77 g/cm^3	$5.1\%/(E[GeV])^{1/2}$	12kY/cc

The assembled forward calorimeter with 8x5 segments of PbF2 crystal ($2.5x2.5x14cm^3$) is shown in Figure 2. We have tested the performance of PbF2 calorimeter at ELPH, Tohoku University and achieved 5% energy resolution, which is among the best performance recorded. The actual experimental setup is shown in Figure 3, with PbF2 calorimeter installed in front of CDS spectrometer.

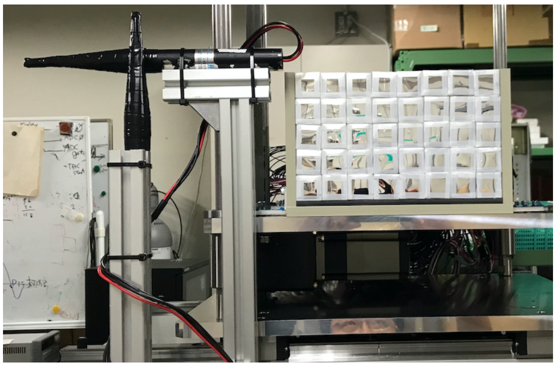

Figure 2. Assembled forward calorimeter.

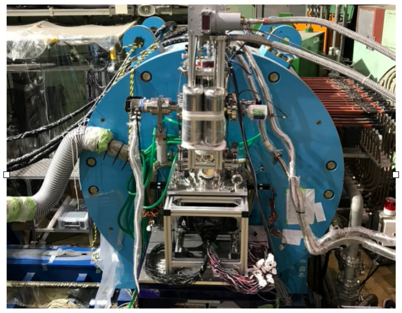

Figure 3. Experimental setup. The forward structure is for cryogenic system and PbF2 calorimeter; the blue barrel is the CDS magnet yoke.

４．研究成果

Our experimental proposal has been approved as J-PARC E73 experiment. 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) with liquid ^{4}He target because of higher signal to noise ratio than ^{3}He. As shown in Figure 4, with 3 days of beam time at 50 kW, we were able to collect a world record of ~1k $_\Lambda^4$H events with 2 times higher statistics and ~10 times better signal to noise ratio [7]. This result demonstrates the feasibility of our new method without any doubt. Our new approach may also find application for other experiments need π^0 identification, for instance, neutron-rich hypernuclear gamma-ray spectroscopy and so on. The lifetime analysis for $_\Lambda^4$H is on-going.

As the second stage, the hypertriton production cross section measurement has been completed in May 2021. We have successfully observed π^- from both 2-body and 3-body decay of hypertriton ground state. This observation provides the first direct determination of the ground state spin of hypertriton as 1/2. Though detailed data analysis is still on going, we are optimistic to obtain the hypertriton binding energy and 2-body to 3-body branching ratio with our recently collected data.

To finally complete this project and solve the hypertriton lifetime puzzle, we have to wait for the beam time, which is most likely to be scheduled in 2023 because of the J-PARC main ring upgrade plan in 2022. However, with the success of the first two stages, we are not expecting any essential problem from now on.

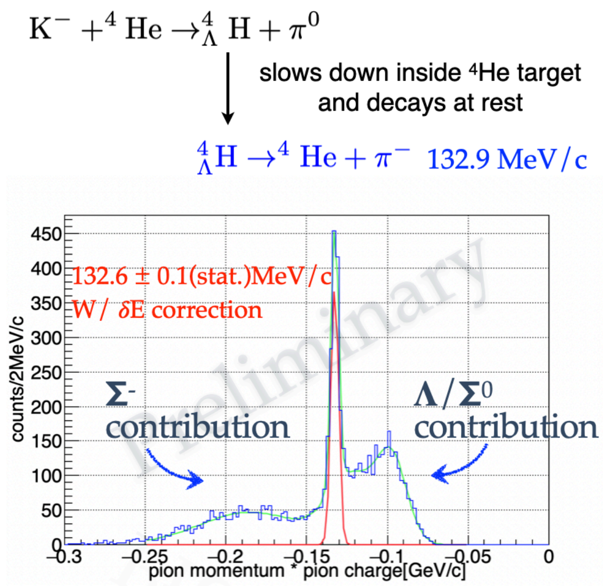

Figure 4. pion momentum distribution from $_\Lambda{}^4H \to {}^4He+\pi^-$ 2-body decay together with continuous background from quasi-free hyperon decay.

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５．主な発表論文等

〔雑誌論文〕　計0件

〔学会発表〕　計4件（うち招待講演　0件／うち国際学会　1件）

１．発表者名
Yue MA

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Towards solving the hypertriton lifetime puzzle with direct lifetime measurement: current status of J-PARC E73 experiment

３．学会等名
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４．発表年
2021年

１．発表者名
赤石 貴也

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３．学会等名
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４．発表年
2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関