Test beam proposal for the J-PARC P73:

Feasibility study for ${}^{3}_{\Lambda}$H mesonic weak decay lifetime measurement with ^{4}He(K^{-}, π^{0})${}^{4}_{\Lambda}$H reaction[1]

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Executive Summary

In J-PARC P73, We have proposed a direct measurement for ${}^{3}_{\Lambda}$H hypernucleus MWD lifetime with ~20% resolution. As the first step for this project, we will measure ${}^{4}_{\Lambda}$H hypernucleus lifetime to demonstrate the feasibility of our experimental approach. The major parameters are summarized below:

Reaction	:	^{4}He(K^{-}, π^{0})${}^{4}_{\Lambda}$H reaction
Secondary beam	:	1.0 GeV/c K^{-}
Beam line	:	K1.8BR
Target	:	liquid ^{4}He
Detector	:	Cylindrical Detector System (CDS) and PbF_2 γ-ray calorimeter
Beam time	:	1 day for detector commissioning
	:	50 kW × 6 days for production run

Contents

1 Introduction to J-PARC P73 and mission for the test beam

1.1 J-PARC P73 experimental setup

As a very loosely bound system, hypertriton($^{3}_{\Lambda}$H, B_{Λ}=130±50 keV[1]) is expected to have a similar lifetime as free Λ hyperon (τ =263.2±2.0 ps). However, two heavy ion experiments(STAR[2], HypHI[3]) found surprisingly short lifetime for $^{3}_{\Lambda}$H as 142^{+24}_{-21}(stat.)±29(syst.) and 183^{+42}_{-32}(stat.)±37(syst.), respectively. Another heavy-ion based experiment, ALICE, previously announced a short hypertriton lifetime as 181^{+54}_{-39}(stat.)±33(syst.) but recently updated their result as 242^{+34}_{-38}(stat.)±17(syst.)[4][5]. It is now apparent that in order to pin down the controversy for hypertriton lifetime, a new test with complementary experimental setup is indispensable. Therefore, we proposed an independent approach to carry out a direct measurement for hypertriton lifetime in time domain.[2]

In J-PARC P73, we will use a novel production method to convert a proton into Λ hyperon as p(K^-, π^0)Λ at 1.0 GeV/c beam momentum. The forwardly boosted projectile π^0 (~0.9 GeV/c) decays almost immediately into two γ rays, which are also forwardly boosted. According to our simulation, by tagging a single γ ray with higher energy in the very forward angle, one can effectively select the ^{3}He(K^-, π^0)$^{3}_{\Lambda}$H reaction[3]. A Cherenkov based compact calorimeter (PbF_2 crystal) with reasonable acceptance and energy resolution will be used for this purpose. After accumulating the hypertriton, we can analyze the π^- decayed from two-body mesonic weak decay, $^{3}_{\Lambda}$H→^{3}He+π^-, by CDS spectrometer.

The schematic experimental setup 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 $^{3}_{\Lambda}$H hypernuclei[9]; the PbF_2 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 $^{3}_{\Lambda}$H and quasi-free Λ and Σ background. For details, please refer to J-PARC P73 full proposal.

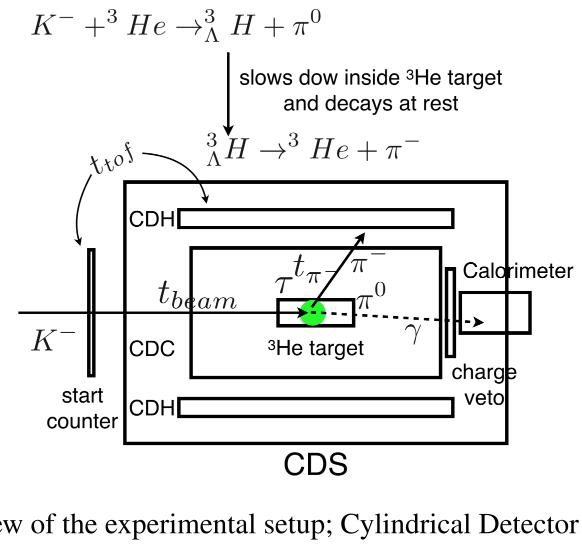

Figure 1: Schematic view of the experimental setup; Cylindrical Detector System(CDS) is used to capture delayed π^- particle from $^{3}_{\Lambda}$H weak decay; high-energy γ rays ($E_\gamma \geqslant 600$ MeV) are tagged with PbF_2 calorimeter.

[2]The heavy-ion experiment needs to convert the decay length into the lifetime; the direct measurement we proposed doesn't need such conversion, which can give an independent test as a complementary method.

[3]Quasi-free Λ production will be a major contamination. In case of $^{3}_{\Lambda}$H two-body mesonic weak decay, one can use the mono-energetic π^- (114 MeV/c) to identify the signal from background. Details are given in J-PARC P73 full proposal.

1.2 Mission for the J-PARC P73 test beam

The mission for the proposed test beam with ^{4}He(K$^-$, π^0)${}^4_\Lambda$H reaction can be outlined as followings:

- Verification of experimental concept
- Background yield measurement
- Systematic error confirmation

As far as we know, J-PARC P73 is the first experiment using calorimeter *along meson beam line* to tag π^0 by capturing high energy γ rays. The calorimeter is expected to have a high hit rate up to 10^6. Though detailed simulation has been performed, real beam test is still mandatory to verify the experimental concept. In addition, J-PARC P73 doesn't use a full brute force neutral meson spectrometer to measure the missing mass. One has to demonstrate with a known case that the proposed semi-inclusive production method actually works. For instance, the main uncertainty in J-PARC P73 is the background yield estimation as illustrated in Fig.2. Depends on the method used in the estimation, the S/N ratio can be several times different. Because most of the contamination is from the quasi-free Λ populated in p(K$^-$, π^0)Λ reaction, we can use liquid ^{4}He to actually measure the background yield, which should be very similar to the ^{3}He case. Therefore, we propose a one week test beam time with liquid ^{4}He target and use ${}^4_\Lambda$H as a test case to verify the experimental method and confirm the systematic error[4].

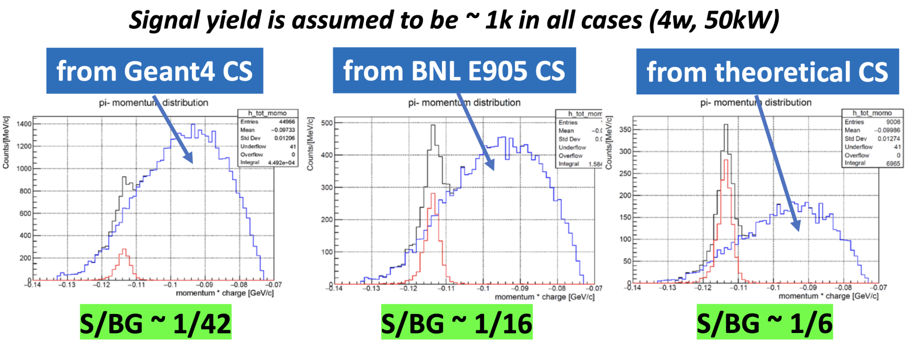

Figure 2: Uncertainty in background yield estimation for J-PARC P73. Left result is obtained by GEANT4 simulation with liquid hydrogen target and scaled to equivalent ^{3}He luminosity; middle plot is based on BNL-E905 results after taking into account the effect of isospin and different beam momentum; right figure is given by theoretical calculation from Prof. T. Harada[7].

Besides the known lifetime, the ${}^4_\Lambda$H also has a better S/N ratio than ${}^3_\Lambda$H and we can learn something with much shorter beam time. The reason can be briefly outlined as the followings: in BNL-E905 experiment, the differential cross section of ^{4}He(K$^-$, π^-)${}^4_\Lambda$He reaction with 0.6GeV/c K$^-$ beam was found to be ~3.5mb/Sr at 4 degree [8]; after taking into account the effect of isospin coupling and recoiling momentum, the differential corss section for ^{4}He(K$^-$, π^0)${}^4_\Lambda$H reaction with 1.0GeV/c K$^-$ beam can be guestimated to be ~ 0.4mb/Sr; in the mean while, the calculated ^{3}He(K$^-$, π^0)${}^3_\Lambda$H cross section is ~0.15mb/Sr[7]. So that ${}^4_\Lambda$H has three times higher production cross section than ${}^3_\Lambda$H. If we further taking into account the factor of 2 from the two-body π^- decay branching ratio between ${}^4_\Lambda$H(b.r. = 50%) and ${}^3_\Lambda$H(b.r.=25%), we can expect that ${}^4_\Lambda$H has ~6 times more signals than ${}^3_\Lambda$H with the same luminosity. As can be read from our full J-PARC P73 proposal, ~1.3k ${}^3_\Lambda$H events will be collected with 4 weeks

[4]The lifetime of ${}^4_\Lambda$H has been measured to be 194^{+24}_{-26} by [6].

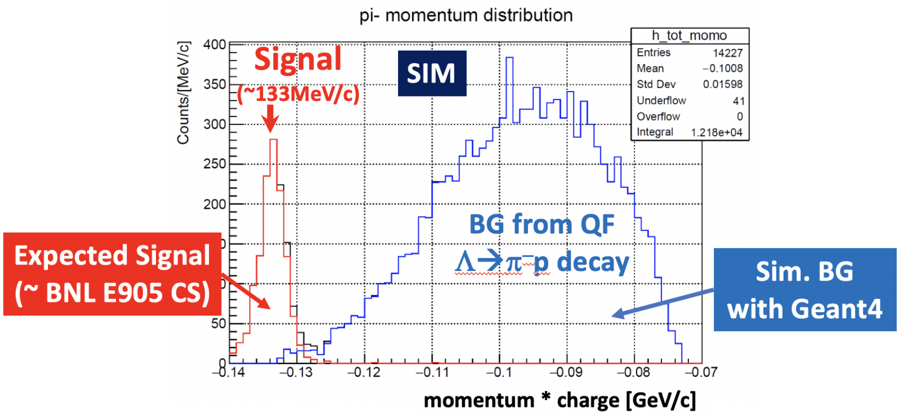

Figure 3: Expected signal and background distribution for ${}^{4}\mathrm{He}(\mathrm{K}^{-}, \pi^{0})^{4}_{\Lambda}\mathrm{H}$ with 6 days data taking at 50kW.

beam time. With the arguments mentioned above, we can expect $\sim$1.8k events from ${}^{4}_{\Lambda}\mathrm{H}$ hypernucleus with one week beam time. It is also worth to address that the S/N for ${}^{4}_{\Lambda}\mathrm{H}$ case will also be better because the π^{-} peak position ($\sim$133MeV/c) is away from the contamination and the background yield will be a quarter of the ${}^{3}_{\Lambda}\mathrm{H}$ case as shown in Fig.3. Therefore, we could effectively study the feasibility in one week beam time with ${}^{4}\mathrm{He}$ target.

2 Preparation status

2.1 CDS tracker

The proposed experiment is, in principle, a semi-inclusive measurement. The momentum resolution for π^- is the key factor for a successful identification for the production of ${}^{3,4}_{\Lambda}$H hypernuclei. We will use Cylindrical Detector System (CDS) originally designed for J-PARC E15 experiment for its demonstrated good performance. The CDS consists of a solenoid magnet, Cylindrical Drift Chamber (CDC) and a hodoscope made of plastic scintillator (CDH). For details, please refer to [9]. The momentum resolution of CDS is given in Fig.4, which is obtained with 0.7 T magnetic field[10]. The transverse momentum resolution for the interested region (p_{π^-}=114 MeV/c) is as good as ∼1.5%. For π^- momentum lower than 110 MeV/c, the resolution becomes worse rapidly because of the energy loss of charged π^- inside target materials. This can be improved by correcting for the energy loss inside the CDS. According to our simulation, a total momentum resolution of ∼2% can be achieved without major modification of the current setup. During last J-PARC E57 beam time, we have confirmed that the main part of CDS was in good condition and ready for data taking.

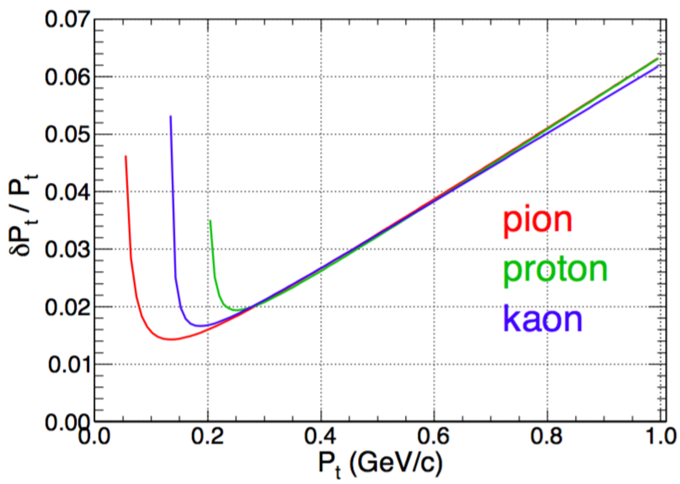

Figure 4: Momentum resolution of CDS [9].

2.2 PbF_2 calorimeter

The most challenging task for the ${}^{3}_{\Lambda}$H production with (K^-, π^0) method is to identify the ground state of ${}^{3}_{\Lambda}$H hypernuclei, which involves the detection of π^0 particle. The outgoing π^0 decays into two γ rays almost immediately. The fast π^0 at the forward scattering angle boosts the decayed γ rays in forward direction. For π^0 with momentum of ~0.9 GeV/c and θ_{π^0}=0, the opening angle between decayed γ rays is centered between $\pm 8^0$. By covering the 0^0 ~8^0 region of polar angle, we can tag the γ ray decayed from π^0 with higher energies.

One can expect very high rate from the unreacted beam hitting on the forward γ-ray calorimeter. We have to construct a calorimeter with high radiation hardness and ultra-fast signals. After searching for materials available on the market, we decide to use PbF_2 crystal as Cherenkov based γ-ray calorimeter. In the J-PARC P73, we will use 40 pieces (5×8 layout) PbF_2 segments with $2.5 \times 2.5 \times 14$ cm^3 dimension (15 radiation length). All 40 pieces of PbF_2 crystals have been delivered from the Shanghai Institute of Ceramics by Spring, 2019. The Hamamatsu H6612 photo-multiplier as readout devices have been delivered and calibrated. By the time of this document is being prepared, the detector assembly has been completed and ready for in-beam calibration at Tohoku University.

The remaining tasks for the the calorimeter are scheduled as below:

- 2019 Dec., calorimeter energy calibration with positron beam at ELPH, Tohoku University: in order to achieve a *ready-to-go* state by the beginning of 2020, we will calibrate the PbF_2 calorimeter with positron beam. Totally 60 hours beam time have been approved and all crystals will be calibrated with a detailed beam energy scan. The assembled calorimeter is shown in Fig.5.

- 2020 Jan., residual field suppression verification: we have carried out a TOSCA simulation for the residual field of CDS solenoid magnet. Without any shielding, the residual field is ~50 Gauss around the photo-multiplier region, which has been confirmed with a recent measurement as shown in Fig.6. After applying the magnetic shielding with 1 cm thick ion, the remaining field will be reduced by half along the PMT longitudinal direction. Though still not perfect, we can verify the performance of PMT in the Jan. of 2020. Further activity such as active magnetic cancelation will be employed if necessary.

By the beginning of 2020, the calorimeter system will be ready to take the experimental data.

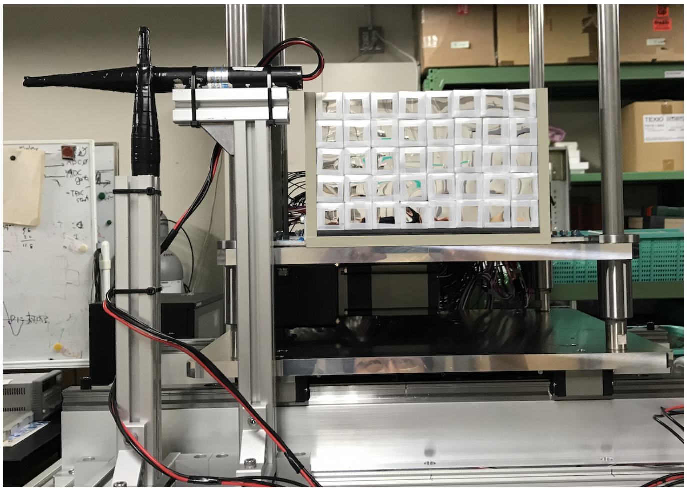

Figure 5: Assembled PbF_2 calorimeter with two finger counters as trigger for calibration at ELPH, Tohoku University in Dec. 2019.

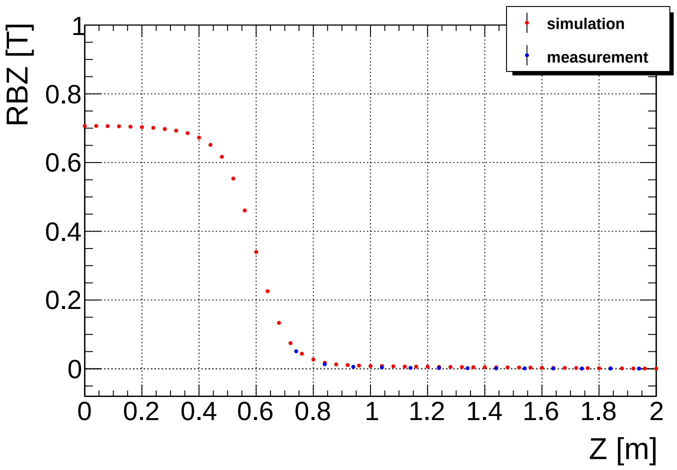

Figure 6: Measurement and TOSCA simulation for CDS residual magnetic field. The blue data points are measurement results; red points are from TOSCA calculation, which agrees well with the measurement.

2.3 Target system

We are developing a new liquid helium target system, whose design is shown in Fig. 7. The concept is very similar to that used in J-PARC E13 experiment. We will use a pulse tube refrigerator PT410 manufactured by CRYOMECH, instead of a GM cryocooler used in E13. Because PT410 has a higher cooling power at 3K, it is more suitable when we use not only helium-4 but also helium-3 as a target. The horizontal structure is to place the target at the center of CDS. In addition, we need to keep space for the PbF2 calorimeters at the exit of the solenoid magnet. This design is also based on the E13 system. The target cell, made of beryllium, will be the same one used in E15.

We already confirmed a basic performance of the cooling system without the horizontal part. We achieved the lowest temperature of 2.5K and ~1 W cooling power at 4K, which is consistent with the specification sheet provided by CRYOMECH. All the components of the horizontal structure will be delivered by the middle of January, 2020. We will assemble them and perform cooling tests at the KEK-Tsukuba campus, and transfer the system to J-PARC by the end of JFY2019. We do not expect any difficulties to be in time for the expriment since we use only established techniques and robust components.

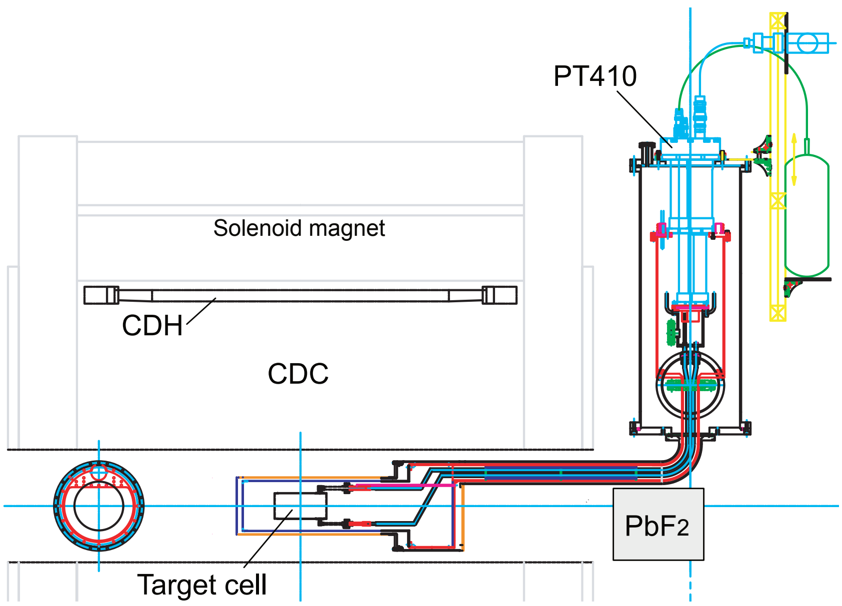

Figure 7: Design of the target system for P73.

3 Beam time request

Based on the estimation described in the previous sections, we require in total 7 days beam time with 50 kW beam power. The details for the beam time schedule is listed as:

Detector commissioning	:	1 day
${}^{4}_{\Lambda}$H production	:	6 days

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