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Experimental status toward the direct lifetime measurement of Hypertriton using the (K^-, π^0) reaction at J-PARC

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In order to shed light on hypertriton lifetime puzzle, we will measure the hypertriton lifetime in time domain directly as an independent and complementary approach from heavy-ion experiments. We employ the (K^-, π^0) reaction to populate hypertriton using a K^- beam at J-PARC. By detecting a high-energy gamma-ray decaying from π^0 at forward angle, this reaction can be tagged efficiently. We newly developed PbF_2 calorimeter and the performance was evaluated with positron and hadron beams. We found that the energy resolution is $\sigma/E = 5.0\ \%/\sqrt{E/GeV}$, which is sufficient for the high-energy gamma-ray tagging in our experiment.

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1. Introduction

The hypertriton($^3_\Lambda$H) is the lightest hypernucleus consisting of a proton, a neutron, and a Λ hyperon. Its properties provide an important benchmark in hypernuclear physics. As a very loosely bound system, the hypertriton(B_Λ = 130±50 keV[1]) is expected to possess a similar lifetime as free Λ hyperon (τ = 263 ps). In 2010s, the lifetime of hypertriton in heavy-ion experiments (HypHI[2], ALICE[3] and STAR[4]) has been found to be 30–40 % shorter than expectation. This has been recognized as the hypertriton lifetime puzzle. Recently, ALICE[5] and STAR[6] collaboration have reported the updated results, which are comparable with free Λ lifetime. However, the Hypertriton lifetime puzzle is still not solved. The hypertriton lifetime should be measured as an independent and complementary approach from heavy-ion experiments.

2. Experimental method in J-PARC E73

Our proposal has been approved as the E73 experiment at Japan Proton Accelerator Research Complex in (J-PARC) in Japan[7]. The E73 experiment employs the (K^-, π^0) reaction to populate hypertriton. The reaction equation is given below.

$$K^- +^3 \mathrm{He} \rightarrow^3_\Lambda \mathrm{H} + \pi^0, \quad ^3_\Lambda\mathrm{H} \rightarrow^3 \mathrm{He} + \pi^-$$

This reaction is a novel production method to convert a proton into Λ hyperon by detecting one of the two gamma-rays decayed from π^0 meson. The high energy gamma-ray (>500 MeV) decayed from the forward projectile π^0 is used to tag Λ hyperon productions with smaller recoiling momentum, which has higher formation probability of hypertriton. These high energy gamma-ray are detected by the calorimeter installed in the downstream of the beamline, together with two layers of plastic scintillation counters for the charged-particle rejection. Hypertriton events can be identified with mono-energic π^- at 114.3 MeV/c from two-body mesonic weak decay, which is measured by a cylindrical detector system (CDS) developed for an experiment to search for kaonic nuclei[8]. CDS is composed of a solenoid magnet, a drift chamber and timing counters. The lifetime of hypertriton can then be derived from the time difference between a start counter and stop counter after subtracting TOF obtained from tracking. The advantage of this approach is that it allows us to carry out a direct lifetime measurement, which is different from the heavy-ion experiments.

3. Design of the Gamma-ray calorimeter

We decided to use the PbF_2 crystal, a Cherenkov light-based calorimeter[9]. The PbF_2 crystal possesses good radiation hardness and generates very fast signal with duration of ~20 ns because of its Cherenkov nature. It is good for installation on the beamline that received the beam directly. Also, for our experiment, PbF_2 have a sufficient energy resolution. Table1 summarizes related properties of PbF_2 crystal.

Figure 1 (a) shows a picture of a single segment before wrapping with a reflection sheet. The PbF_2 crystal, produced by Shanghai Institute of Ceramics, has a $2.5\times2.5\times14\mathrm{cm}^3$ dimension, which corresponds to ~15 radiation length along the beam direction. The crystal is wrapped with a sheet

Table 1: Properties of the PbF_2 crystal [9].

Crystal	Radiation length	Moliere radius	Density	Refractive index	Energy resolution
PbF_2	0.93 cm	2.22 cm	7.77 g/cm^3	1.82	5.1 % /$\sqrt{\mathrm{E/GeV}}$

of aluminized Mylar, and coupled to a 1/4-inch photo-multiplier (PMT, Hamamatsu H6612B) with a UV-curable resin.

Figure 1 (b) shows the calorimeter assembly. We use 40 segments arranged in the 5 (vertical) $\times$ 8 (horizontal) layout. Thus, the total effective area is 12.5 cm (vertical) $\times$ 20.0 cm (horizontal). The calorimeter placed ~85 cm downstream from the target center, covering 0°–8° region of polar angle. At the calorimeter position, the fringing field of the solenoid magnet was measured to be 1.18 mT. Therefore, the crystals and PMTs are surrounded by 1 cm thick iron as a magnetic field shield. With this magnetic shield, the fringing field was suppressed to 0.09 mT, and no gain change in the PMT was observed with and without solenoid field.

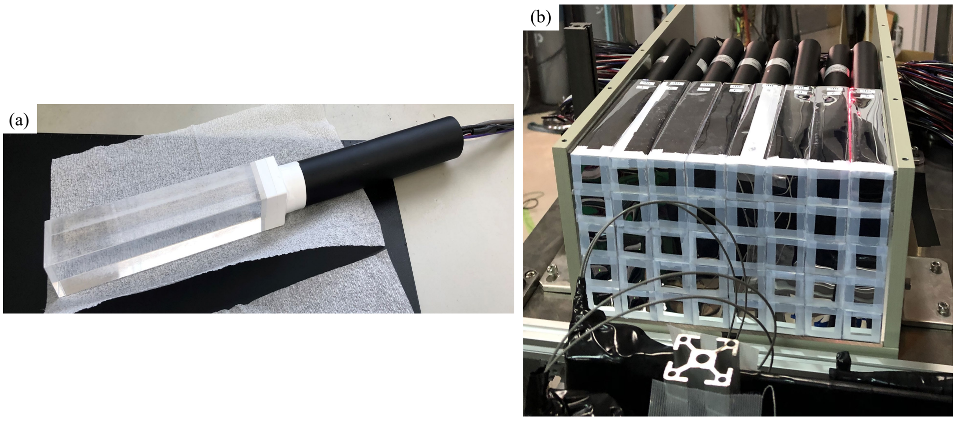

Figure 1: (a) Picture of a single segment. (b) Picture of the 40-segments array surrounded by the iron magnetic shield (without the top plate).

4. Performance evaluation of the calorimeter

We evaluated the performance of the PbF_2 calorimeter using a positron beam at Research Center for Electron Photon science (ELPH), Tohoku University in Japan, and a hadron beam at J-PARC. Table2 summarizes two test experimental condition.

Table 2: Summary of test experimental condition

Facility	Beam line	Beam particle	Beam momentum	Reflective material	Period
ELPH	GeV-γ	e^+	0.1–0.8 GeV/c	ESR	Dec. 2019
J-PARC	K1.8BR	π^-, e^-	-1.0 GeV/c	Al Mylar	Jun. 2020

At ELPH, we tested the energy response of the calorimeter by using positron beams. The beam energy was changed from 100 to 800 MeV with 100 MeV steps. Two crossing scintillation counters were used as the data-acquisition trigger, which defined the beam position to be at the center of a PbF_2 segment with 5×5 mm^2 size.

The total energy deposited by the beam particle was evaluated by summing up the energies of a primary segment and 8 secondary segments around it in a 3×3 square. Here the primary segment was defined as a segment with the largest energy deposit among 40 segments. In this case, the primary segment is usually the segment just behind the trigger counters.

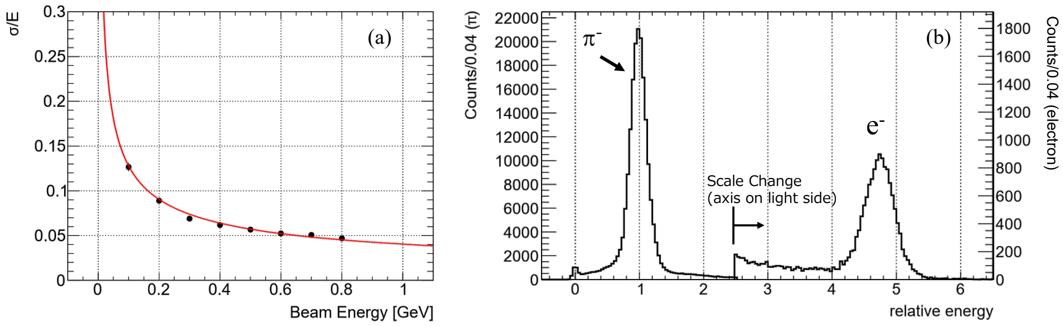

Figure 2: (a)Energy resolution(σ/E) in a 3×3 cluster of ESR-wrapped crystals as a function of positron energy. (b)Spectrum(with pedestal subtracted) for a momentum of 1GeV/c. Note the scale change for the electron peak.

Figure 2 (a) shows the energy resolutions at a typical segment obtained as a function of the beam energy. The incident energy (E) dependence of the energy resolution (σ) can be described by

$$\frac{\sigma}{E} = \frac{a_0}{\sqrt{E/GeV}}. \tag{1}$$

Fits to this function yield a_0 = (4.05±0.03) %. Better energy resolution than 5 % has been obtained. This is as expected.

The performance of the calorimeter in a hadron beam was evaluated at the K1.8BR beamline of Hadron Experimental Facility in J-PARC. The measurement was performed as a part of J-PARC T77 experiment[10], which was to demonstrate the feasibility of the (K^-, π^0) reaction for the hypernuclues production. We used K^- beam at 1 GeV/c for the hypernucleus production. The contaminated π^- and e^- beams can be identified with an Aerogel Cherenkov counter, although our beamline apparatus have no ability to distinguish π^- and e^-.

A typical energy spectrum of the PbF_2 calorimeter irradiated with π^-/e^- beams at 1 GeV/c is shown in Figure 2 (b). The energy calibration is performed using π^--like events by selecting events in which only one segment has a finite energy deposition. The horizontal scale here is a relative one to the peak position of π^- events.

We observed another peak at ~5 times larger energy than the π^- peak. From the calculated Cherenkov light yield in n=1.82, this peak was identified to be e^- events. The ratio of pion peak and electron peak is reasonable. The width of the electron peak was found to 5.0 % in sigma. This value is comparable with the results obtained with the positron beams at ELPH. The small difference might come from the dependence on the incident beam position. Whereas we chose beams on the center of the primary segment at ELPH, the beam position on the primary segment should be uniformly distributed in the J-PARC measurement. Although the reflective material was changed to aluminized mylar from ELPH test-beam, there was no difference when tested and compared with positron.

5. Summary and Outlook

We will propose new measurement of hypertriton lifetime as an independent and complementary approach from heavy-ion experiments. For our experiment, PbF_2 play an important role in tagging hypernuclues production. As a performance evaluation, the energy resolution is σ/E = 5.0 %/$\sqrt{\mathrm{E/GeV}}$ and the PbF_2 crystals have a nice separation between pion and electron. As a current status, we have performed a test experiment with helium-4 target to demonstrate the feasibility of (K^-, π^0) reaction in June 2020. The pilot run with helium-3 target has been carried out in May 2021. We have successfully identified ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H events. For hypertrion lifetime measurement with helium-3 target, we will performed the final data taking run in JFY2022.

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