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Status of a Lifetime Measurement of Light Hypernuclei Using High Intensity Tagged Photon Beam at ELPH

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In this paper we present an overview and preparation status of a hypernulear lifetime measurement using Timing counter for Direct Lifetime measurement (TDL) and a magnetic spectrometer named neutral kaon spectrometer 2 (NKS2) at Research Center of Electron and Photon Science (ELPH), Tohoku University. We show a result of pilot experiment to check a feasibility of our experimental method and describe a plan of a next test experiment.

KEYWORDS: Photoproduction, Strangeness, Hypernuclei

1. Introduction

A systematic study of hypernuclear structures is predominantly used for construction of hyperon-nucleon interaction models because a scattering experiment is not easy to perform due to short lifetimes of hyperons. Particularly, investigation of few body systems such as mass number of A=3 and 4 is important because exact 3- or 4-body calculation can describe the hypernulcear properties without model dependence. However, our understanding of a 3-body hypernucleus, hypertriton (Λ + p + n), is not enough. In 2010s, heavy-ion experiment groups reported that lifetime of hypertriton was about 20% shorter than that of Λ particle [1] [2] [3] [4]. On the other hand, emulsion experiments showed that a hypertriton was a shallow bound state of Λ (binding energy of Λ = 0.13 ± 0.04 MeV [5]). The small binding energy leads to a small overlap between Λ and a deuteron core, and thus, the lifetime of hypertriton is predicted to be almost the same as that of Λ (= 263.2 ± 0.2 ps [6]). The contradiction between the short lifetime and the small binding energy is known as "hypertriton puzzle". Precise measurement of the lifetime of hypertriton can play a key role to solve the hypertriton puzzle because an accuracy of previous lifetime measurements is not enough. We plan to perform an experiment to measure the lifetime with an accuracy of 10 ps using high intensity tagged photon beam at ELPH. Hypertriton will be produced from liquid ^{3}He via the $(\gamma,\ K^+)$ reaction. Lifetime of hypertriton would be deduced from a time difference between a production time measured by photon tagging system and a decay time measured by a new high-time resolution counter. We have performed a feasibility test experiment with a prototype decay timing counter at ELPH in 2017. Now, we are promoting detector construction and detail experimental design.

2. Design of direct lifetime measurement of ${}^{3}_{\Lambda}$H at ELPH

2.1 Experimental method

We are planning to perform an experiment to measure the lifetime of ${}^{3}_{\Lambda}$H at ELPH as real photon beam above the threshold energy of photo-production of ${}^{3}_{\Lambda}$H (= 0.76 GeV) is available. Fig. 1 shows a schematic drawing of the experimental setup. K^+ produced simultaneously with ${}^{3}_{\Lambda}$H is measured by NKS2. Decay π^- from ${}^{3}_{\Lambda}$H will be measured by a detector system around the target. The detector system consists of timing counter, tracking detector and range counter from target side to outside. The detector system is cylindrical shape surrounding the target to have large solid angle.

2.2 Identification of ${}^{3}_{\Lambda}$H

${}^{3}_{\Lambda}$H is identified by massing mass method. Missing mass is calculated by Eq. (1).

$$M_{hyp} = \sqrt{(E_\gamma - E_K + M_A)^2 - (\boldsymbol{p}_\gamma - \boldsymbol{p}_K)^2} \quad (1)$$

$$B_\Lambda = (M_{core} + M_\Lambda) - M_{hyp} \quad (2)$$

M_A is a mass of a target and it is well known. E_γ is an energy of a real photon, measured by the photon tagger. Momentum vector of K^+ is measured by NKS2. Binding energy of Λ particle (B_Λ) is shown as Eq. (2). M_{core} is a mass of core nucleus (deuteron mass), M_Λ is a mass of a Λ particle.

2.3 Method of lifetime determination

Production time of real photon will be measured by a photon tagging system. Decay time of a hypernucleus (t_d) will be deduced from timing of decay particle (t_t) measured by a good timing resolution detector. t_d can be described as follows.

$$t_d = (t_t - ToF_t) - (t_\gamma + ToF_\gamma) \quad (3)$$

Time of flight from target to the detector is defined as ToF_t, time of flight of real photon is defined as ToF_γ. Time resolution of the existing photon tagger system is about 70 ps (σ). It is good enough to measure production timing of ${}^{3}_{\Lambda}$H. We need a new good time resolution detector for decay π^-. Requirements for the timing detector are (1) good time resolution (σ_t < 100 ps), (2) work in a magnetic field, (3) large solid angle ($\sim 4\pi$ sr), (4) compact size to install inside of a tracking detector ($< 110 \times 110 \times 600\text{mm}^3$).

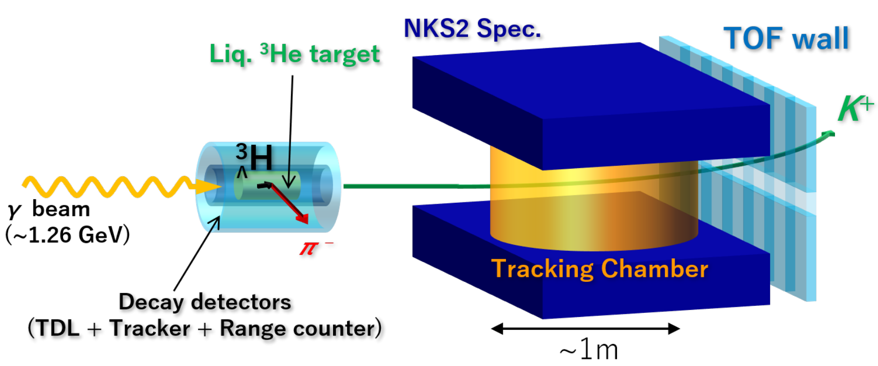


Fig. 1. Setup plan of the experiment. K^+ is measured by the forward magnetic spectrometer, NKS2. π^- from hypernuclei is measured by the decay counters around the target.

3. Phase0 experiment

3.1 Setup

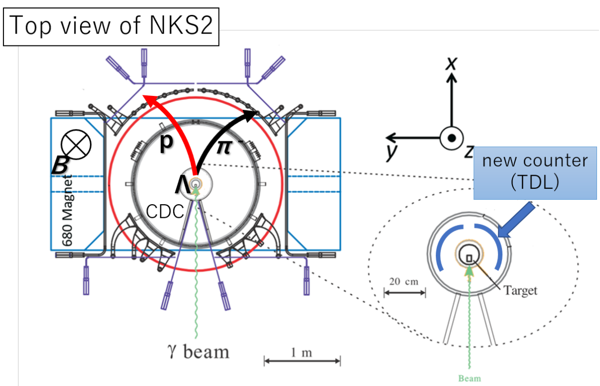
We performed an experiment using a liquid hydrogen target to check a feasibility of our experimental method. Fig. 2(a) shows the schematic drawing of an experimental setup. The hydrogen target was a standard target of NKS2 [7]. Proto-type of TDL was installed at center of the NKS2 magnet to surround the target. TDL was composed of 14 plastic scintillator plates, 28 SiPMs and analog amplifier circuits with high speed ope-amp (Fig. 2(b)). Intrinsic time resolution of TDL was 140 ps (σ). Momentum vectors of charged particles was deduced from trajectory measured by cylindrical drift chamber (CDC) in a magnetic field of NKS2. Λ particles were identified by invariant mass of π^- and proton.

3.2 Result

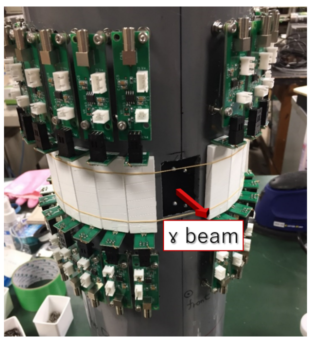
Invariant mass method was used to identify Λ particle. Invariant mass was calculated by Eq. 4. Momentum of proton and π^- were measured by NKS2.

$$M_\Lambda = \sqrt{(E_p + E_\pi)^2 - (p_p + p_\pi)^2} \tag{4}$$

The invariant mass spectrum is shown in Fig. 3(a). Proton and π^- were identified from time of flight (TOF) and momentum information measured by NKS2. Peak region shown by arrows in Fig. 3(a) was selected as Λ decay events. The total number of Λ was about 150. Decay time is shown in Fig. 3(b). Red hatched histogram shows Λ decay time distribution. Blue solid line shows a response function which is obtained from the $\gamma + p \to p + \pi^+ + \pi^-$ reaction. The resolution was 180 ps (σ) and stable during the experimental period of 4 days. Fluctuation of width of response function was less than ±10 ps. Black solid line shows a simulated result of Λ decay events. The simulation includes acceptance effects of the detector, relativistic effects and background effects. Lifetime of background events was assumed 0 s in the simulation since main component of background was non-strangeness process (eg. $\gamma + p \to p + \pi^+ + \pi^-$). Λ decay time spectrum was consistent with the simulation. Detail discussion of systematics doesn't make sense due to low statistics and small acceptance. The radius of prototype TDL was about 80 mm. That small radius made a cut off against long lifetime. However, the purpose of this experiment was observing delay component of hyperon decay. That was achieved.

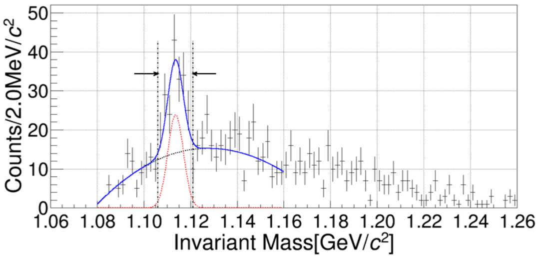


(a) Setup of the phase0 experiment.

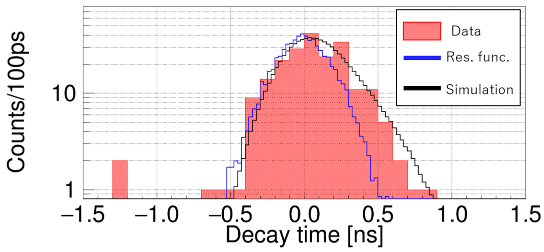


(b) Picture of proto-type TDL.

Fig. 2. (a) Schematic drawing of experimental setup of the phase0 experiment. (b) Picture of proto-type TDL which was composed of 14 plastic scintillator plates, 28 SiPMs and amplifier circuits.



(a) Invariant mass of π^- and proton.



(b) Decay time of Λ particles.

Fig. 3. (a) Invariant mass of π^- and proton. (b) Decay time spectrum of Λ. Red hatched histogram shows data. Blue solid line shows response function which is obtained from $\gamma + p \to p + \pi^+ + \pi^-$ reaction. Black solid line shows simulated result of Λ decay event.

4. Future prospect

4.1 Strategy of TDL project

From the phase0 experiment, we concluded that our experimental method and detectors will work for lifetime measurement of hypernuclei. Now we are developing some new counters and polishing up experimental design. First, the detector system for decay π^- needs to be developed. We also need to update ToF counter and add Cherenkov counters to NKS2 system to start spectroscopy of hypernuclei at ELPH since the separation power between K^+ and π^+ of current NKS2 is not enough. We will start spectroscopy of hypernuclei with ^{4}He target in 2019 as ^{3}He is very expensive and difficult to handle. That experiment will give us a reliable estimation of systematic error of the method since lifetime of $^4_\Lambda$H is already measured at KEK [8]. After that we will perform the experiment using ^{3}He target.

4.2 Next experiment

We are constructing new detector system for decay pions. We will have a commissioning experiment of a few days soon. New TDL is composed of 48 plastic scintillator bars and 96 SiPMs.Each 2 SiPMs were connected in series to reduce the number of read out channels. Intrinsic time resolution was measured to be 100 ps (σ) with cosmic ray. TDL will be combined with vertex drift chamber (VDC) [7] used in previous NKS2 experiment. CH_x target will be used in this experiment instead of He target. In the next experiment, we will study about decay time spectrum measured by new TDL, missing mass resolution, vertex resolution of VDC and trigger rate.

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