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Known and exotic light hypernuclei studied with the ^{6}Li+^{12}C reaction at 2 A GeV

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Abstract. Light hypernuclei have been studied by using induced reactions of ^{6}Li projectiles bombarded on the natural carbon target by means of the invariant mass method, and $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H hypernuclei as well as Λ-hyperons are produced and identified. Significance values of $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H and Λ are respectively 4.7σ, 4.9σ and 6.7σ. By analyzing decay vertices of $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H and Λ by means of unbinned maximum likelihood fitting their lifetime values have been deduced to be 183^{+42}_{-32} ps, 140^{+48}_{-33} ps and 262^{+56}_{-43} ps, respectively. In addition, signals appeared for the d+π^- and t+π^- final states in the analyses on invariant mass and lifetime. Those signals have suggested a possible bound state of two neutrons with Λ, $^{3}_{\Lambda}$n. It has also been revealed for the first time that the lifetime of $^{3}_{\Lambda}$H is significantly shorter than that of Λ, which is consistent to the statistical analyses including all the lifetime data reported in the past. However, there is no theoretical model to explain the short lifetime of $^{3}_{\Lambda}$H as well as the existence of the $^{3}_{\Lambda}$n bound state. These should be further experimentally and theoretically studied.

1. Introduction

One of the important issues in nuclear and hadron physics is the comprehensive understanding of baryon-baryon interactions under the flavor SU(3) symmetry with up, down and strange quarks. A baryon involving at least one strange quark is called a hyperon, and the lightest hyperon is Λ. Because the Λ-hyperon decays via weak interaction with a lifetime of 263.2 ps [1], it has not been practical to study the nucleon-Λ and Λ-Λ interactions by direct reaction experiments with projectiles and targets involving the Λ-hyperon, thus a Λ-hypernucleus, a bound subatomic system containing a Λ, was studied to extract information on the nucleon-Λ and Λ-Λ interactions. About 40 kinds of Λ-hypernuclei have been so far investigated experimentally mainly with emulsion techniques [2], secondary meson beams [3] and primary electron beams [4]. In those experiments, the isospin of the produced hypernuclei was limited by the reaction mechanism since a nucleus in the stable target material is converted to a Λ-hypernucleus by production or exchange of strangeness in a single nucleon. While, a different approach to studying hypernuclei by using projectile fragmentation reactions of heavy ion beams was employed for the present work. In such reactions, a projectile fragment can capture a hyperon produced in the hot participant region to produce a hypernucleus. In this reaction, the produced hypernucleus has a large Lorentz factor, and the decay of the hypernucleus takes place well behind the production target. This makes it possible to study hypernuclei in flight. Since a hypernucleus is produced from a projectile fragment, isospin and mass values of the produced hypernuclei, unlike in other hypernuclear experiments, can be widely distributed in similar fashion.

The HypHI collaboration has proposed a series of experiments at the GSI Helmholtz Centre for Heavy Ion Research, using induced reactions of stable heavy ion beams and rare-isotope beams, with the aim of producing and measuring hypernuclei with an invariant mass method [5]. In the proposed experiments, charged particles and neutrons from the mesonic or non-mesonic weak decay of hypernuclei are tracked and identified in order to reconstruct the hypernuclear mass values. The lifetime of produced hypernuclei can be extracted by measuring of the proper time in the rest frame of the hypernuclear decay. This methodology also allows investigating neutron- and proton-rich hypernuclei as well as hypernuclei with more than two units of strangeness, and several hypernuclei can be studied in a single data taking.

The first experiment aiming to study ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H hypernuclei was performed by mean of projectile fragmentation reactions of ^{6}Li projectiles at 2 *A* GeV delivered on a carbon target. In the experiment, we have succeeded to observe signals of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H as well as those in the d+π^- and t+π^- as the final states. The later two signals may indicate the existence of a possible bound state of two neutrons and a Λ-hyperon (${}^{3}_{\Lambda}$n). In this article, we discuss on the observation of these signals. The discussions below are based on our already published articles [6, 7, 8].

2. Experiment

The first HypHI experiment, Phase 0, took place at the GSI Helmholtz Centre for Heavy Ion Research. Details of the experimental setup and analyses can be found in [6]. Projectiles of ^{6}Li at 2 *A* GeV with an average intensity of 3×10^{6} beam particle per second were propelled at a carbon graphite target 8.84 g/cm^2 thick. As discussed in [6], the experimental apparatus consisted of three tracking stations of scintillating fiber detector arrays, (*TR0, TR1, TR2*), and two drift chambers (*BDC, SDC*) for the displaced vertex measurement. As well, three scintillating hodoscope walls (*TOF+, TFW, ALADiN TOF*) were appended to the tracking systems for tracking, energy loss and time-of-flight measurements of charged particles across a large acceptance dipole magnet. The tracking system for vertexing was placed in front of the dipole magnet around the expected decay volume of hypernuclei, while the *SDC* drift chamber was set just behind the magnet. Two detached detection branches consisting of *TOF+* and *TFW & ALADiN TOF* hodoscope walls were situated behind the magnet in such a way to measure separately positively and negatively charged particles respectively.

At the trigger level, the event topology was selected in order to acquire and record potential events combining a displaced vertex, a Helium isotope and a π^- meson as decay particles. The displaced vertex trigger used the information of *TR0*, *TR1* and *TR2* fiber detector arrays around the decay volume of hypernuclei and Λ hyperons. The Helium isotope trigger used the time-over-threshold measurement of the energy loss from the *TOF+* hodoscope wall dedicated solely for the positively-charge particle and fragments. The π^- trigger involved the hit detection on the *TFW* hodoscope wall dedicated exclusively for π^- detection behind the dipole magnet.

This topological combination at hardware level was exploited in order to cope with the large difference of magnitude between the hypernuclear production cross section and the total reaction cross section.

The particle identification was based on the track reconstruction across the magnet, the measurements of the time-of-flight, and the energy deposit with the hodoscope walls. The four-vectors of the detected particles and fragments were then deduced. The invariant mass of final states of interest was calculated and a lifetime estimation was inferred from the observed decay vertex position after the decay vertex finding. Details of the analyses are discussed in [6].

3. Results

After the particle identification and the reconstruction of the decay vertexes, the invariant mass of the final states of interest has been deduced. Details of the analyses can be found in [6, 7]. The top panels of Figure 1 show the invariant mass distributions for p + π^-, ^{3}He + π^- and ^{4}He + π^- candidates. In each distribution, a peak at around the mass of Λ, $^3_\Lambda$H and $^4_\Lambda$H can be seen. The background contributions to the invariant mass distributions initially were estimated with the event mixing method [9, 10]. The background contribution estimated via mixed event analysis is shown in Figure 1 by the open triangles. The separated signal and background contributions have been estimated via the binned maximum likelihood fitting method. A signal in the invariant mass distributions is represented by a Gaussian probability density function. The background contribution was then modeled by a Chebychev polynomial probability density function of the first kind. An extended maximum likelihood estimator allowed us to obtain the share of signal and background in each invariant mass spectrum. Significance values of the signals are 6.7σ, 4.7σ and 4.9σ for Λ hyperon, $^3_\Lambda$H and $^4_\Lambda$H, respectively.

After reconstructing the invariant mass, the lifetime of Λ, $^3_\Lambda$H and $^4_\Lambda$H was extracted. The signal contribution was determined by subtracting the background contribution from the signal-plus-background contribution. For this purpose, two data sets are built. The signal-plus-background contribution was deduced in the fitted peak region within the fitted values of $\bar{m} \pm 2\sigma_m$, and the background-only data set was extracted from the adjacent sideband region within the intervals of $[\bar{m} - 4\sigma_m, \bar{m} - 2\sigma_m]$ and $[\bar{m} + 2\sigma_m, \bar{m} + 4\sigma_m]$ with proper normalization. In each data set, the proper decay time $t = l/(\beta\gamma\, c)$ is then calculated in the rest frame of the mother state of interest from the measured decay length l, where $\beta\gamma\, c = p/m$, p and m the momentum and the mass of the mother state of interest. The yield at different decay lengths was also corrected by the deduced acceptance and reconstruction efficiency based on full Monte Carlo simulations. The lifetime values were then extracted utilizing an *unbinned* maximum likelihood fitting method. The profiled likelihood ratios for estimation of the mean decay length $c\tau$ of Λ hyperon, $^3_\Lambda$H and $^4_\Lambda$H hypernuclei are shown in the middle panels of Figure 1. Deduced lifetime values for Λ, $^3_\Lambda$H and $^4_\Lambda$H are respectively 262^{+56}_{-43} ps, 183^{+42}_{-32} ps and 140^{+48}_{-33} ps. The goodness of the fitting was represented by the χ^2 test by using the modeled proper decay time function with the background [6], and they are shown in the bottom panels of Figure 1.

Analyses with the same manner were applied for all possible final states, and all the final states were investigated. Surprisingly. signals involving the d+π^- and t+π^- final states have been appeared [7], as shown in panels (a1) and (a2) of Figure 2. Significance values of these signals are respectively 5.0 σ and 5.3 σ. The lifetime values of the state finalizing to d+π^- and t+π^- have been deduced in the same manner for Λ, $^3_\Lambda$H and $^4_\Lambda$H, and they are respectively 181^{+30}_{-24} ps and 190^{+47}_{-35} ps [7]. The results of the lifetime analyses are also shown in Figure 2.

After the careful investigations of possibility of creating artificial peaks and the mis-reconstruction of multi-body decays of the other hypernuclei [7], we have suggested that those signals are from the two- and three-body decays of an unknown neutral hypernuclear bound state with two neutrons and one Λ-hyperon, $^3_\Lambda$n [7].

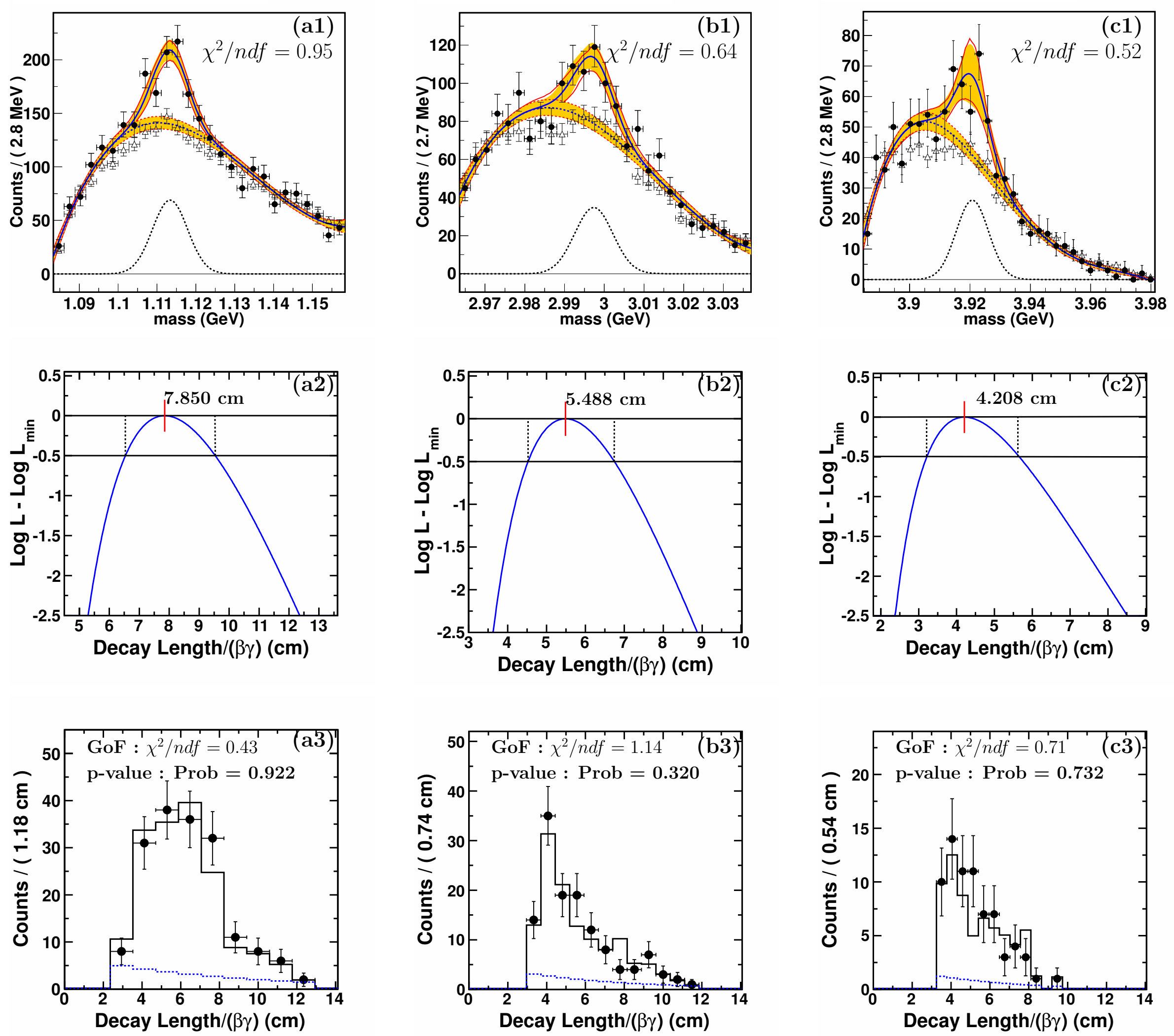

Figure 1. (Color online) Invariant mass distribution for candidates of Λ, ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H, are represented by the filled circles in panels (a1), (b1), and (c1), respectively. The shaded orange region represents one standard deviation of the fitted model centered at the solid blue line. The dotted lines show the separate contributions of the signal and the background with, respectively, black and colored lines. The data represented by open triangles correspond to invariant mass distributions of the mixed event analysis. Profiled likelihood ratio for interval estimation of Λ hyperon (a2), ${}^{3}_{\Lambda}$H (b2), and ${}^{4}_{\Lambda}$H hypernuclei (c2) is shown. Interval estimation for 1 standard deviation is shown on each profiled likelihood ratio. *Binned* decay length distributions of the signal region of Λ hyperon (a3), ${}^{3}_{\Lambda}$H (b3), and ${}^{4}_{\Lambda}$H hypernuclei (c3) with the fitted model, which included the exponential function resulted from the *unbinned* maximum likelihood fit and the background contribution estimated by the sidebands. The black line represents the fitted model, while the blue dotted line represents the contribution of the exponential function. Figures are taken from [6] and rearranged.

4. Discussion

There are two striking results presented by the current work. First, as discussed above, the lifetime of ${}^{3}_{\Lambda}$H has been observed to be 183^{+42}_{-32} ps, which is significantly shorter than that of the

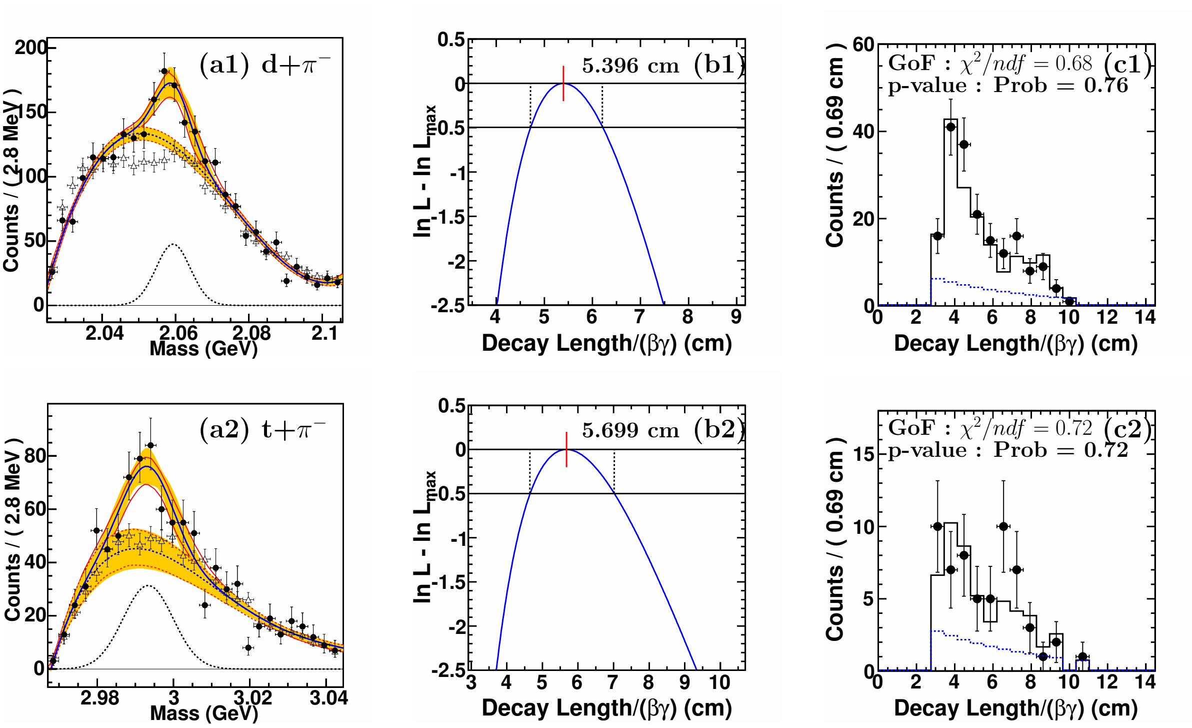

Figure 2. (Color online) Invariant mass distributions of d+π^- final state candidate in panels (a1) and of t+π^- in panels (a2). They are for -10 cm $< Z <$ 30 cm. Profiled likelihood ratio for interval estimation of d+π^- (b1) and t+π^- (b2) as well as *Binned* decay length distributions of the signal region of d+π^- (c1) and t+π^- (c2) are shown. Same convention of the representation of figures in Fig. 1 is used. Figures are taken from [7] and rearranged.

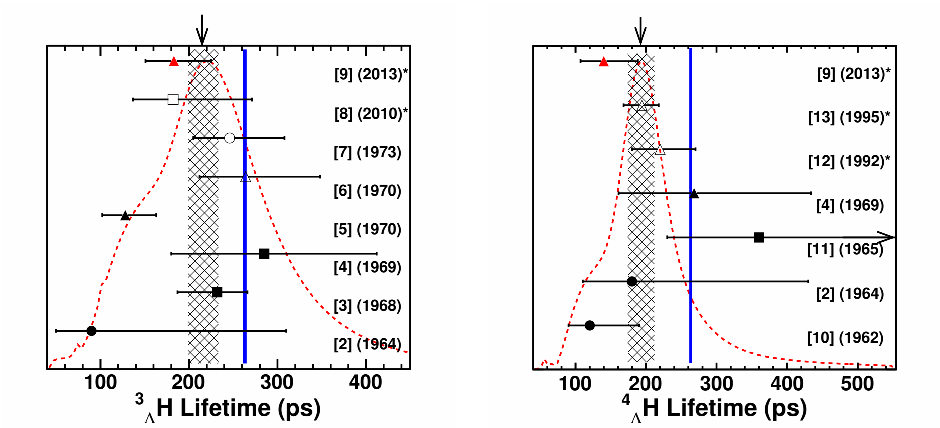

Figure 3. (Color online) World data comparison of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H lifetimes. The combined average is represented by the arrow at the top, while the width of the hatched band corresponds to the one standard deviation of the average. The vertical line at 263.2 ps with width of ± 2 ps shows the known lifetime of Λ hyperon. References to counter experiments is marked by an asterisk. Figures are taken from [8].

Λ-hyperon (263.2 ps). Since the binding energy of the Λ-hyperon to the deuteron core in ${}^{3}_{\Lambda}$H is known to be only 130 keV, it has been expected that the lifetime of ${}^{3}_{\Lambda}$H should not be deviated from that of the Λ-hyperon. However, the lifetime of ${}^{3}_{\Lambda}$H has not been discussed extensively since the experimental data of the ${}^{3}_{\Lambda}$H lifetime was rather scarce and scattered with large errors. We have analyzed all the existing data for the lifetime of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H with statistical methods [8], and the combined analyses have shown that the possible range of the ${}^{3}_{\Lambda}$H lifetime is also significantly lower that the Λ lifetime, as shown in Figure 3. It has to be noted that the short lifetime of ${}^{3}_{\Lambda}$H has also recently been observed by the STAR and ALICE collaborations [11, 12], however, there is no theory to reproduce the observed short lifetime of ${}^{3}_{\Lambda}$H.

After our observation of the signals indicating the possible existence of ${}^{3}_{\Lambda}$n by observing the d+π^- and t+π^- final states, there have been several theoretical calculations to study the bound state of ${}^{3}_{\Lambda}$n [13, 14, 15]. They have shown that it can not be bound by basing on the current theoretical framework. However, it has to be emphasized hereby once again that the current theories can not explain the short lifetime of ${}^{3}_{\Lambda}$H which is a mirror hypernucleus of ${}^{3}_{\Lambda}$n, and therefore, the conclusion of the existence of ${}^{3}_{\Lambda}$n can not yet be given. Both the existence of ${}^{3}_{\Lambda}$n and the short lifetime of ${}^{3}_{\Lambda}$H have to be further experimentally and theoretically studied.

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