Neutron-rich hypernuclei: evidence for6ΛH and search for9ΛHe

Published version:

DOI:10.1051/epjconf/20123701023

EPJ Web of Conferences **37**, 01023 (2012)
DOI: 10.1051/epjconf/20123701023

Neutron-rich hypernuclei: evidence for $^{6}_{\Lambda}$H and search for $^{9}_{\Lambda}$He

M. Agnello[1,2], L. Benussi[3], M. Bertani[3], H.C. Bhang[4], G. Bonomi[5,6], E. Botta[7,2,a], M. Bregant[8], T. Bressani[7,2], S. Bufalino[2], L. Busso[7,2], D. Calvo[2], P. Camerini[9,10], B. Dalena[11], F. De Mori[7,2], G. D'Erasmo[12,13], F.L. Fabbri[3], A. Feliciello[2], A. Filippi[2], E.M. Fiore[12,13], A. Fontana[6], H. Fujioka[14], P. Genova[6], P. Gianotti[3], N. Grion[9], V. Lucherini[3], S. Marcello[7,2], N. Mirfakhrai[15], F. Moia[5,6], O. Morra[2,16], T. Nagae[14], H. Outa[17], A. Pantaleo[13,b], V. Paticchio[13], S. Piano[9], R. Rui[9,10], G. Simonetti[12,13], R. Wheadon[2], A. Zenoni[5,6], and A. Gal[18]

1 Dipartimento di Fisica, Politecnico di Torino, corso Duca degli Abruzzi 24, Torino, Italy
2 INFN Sezione di Torino, via P. Giuria 1, Torino, Italy
3 Laboratori Nazionali di Frascati dell'INFN, via E. Fermi 40, Frascati, Italy
4 Department of Physics, Seoul National University, 151-742 Seoul, South Korea
5 Dip. di Ingegneria Meccanica e Industriale, Università di Brescia, via Valotti 9, Brescia, Italy
6 INFN Sezione di Pavia, via Bassi 6, Pavia, Italy
7 Dipartimento di Fisica, Università di Torino, via P. Giuria 1, Torino, Italy
8 SUBATECH, École des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
9 INFN Sezione di Trieste, via Valerio 2, Trieste, Italy
10 Dipartimento di Fisica, Università di Trieste, via Valerio 2, Trieste, Italy
11 CEA, Irfu/SACM, Gif-sur-Yvette, France
12 Dipartimento di Fisica Università di Bari, via Amendola 173, Bari, Italy
13 INFN Sezione di Bari, via Amendola 173, Bari, Italy
14 Department of Physics, Kyoto University, Sakyo-ku, Kyoto, Japan
15 Department of Physics, Shahid Behesty University, 19834 Teheran, Iran
16 INAF-IFSI, Sezione di Torino, corso Fiume 4, Torino, Italy
17 RIKEN, Wako, Saitama 351-0198, Japan
18 Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

Abstract. The FINUDA experiment at DAΦNE, Frascati, has found evidence for the neutron-rich hypernucleus $^{6}_{\Lambda}$H studying (π^+, π^-) pairs in coincidence from the $K^-_{\rm stop}$+^{6}Li $\rightarrow$ $^{6}_{\Lambda}$H$+\pi^+$ production reaction followed by $^{6}_{\Lambda}$H $\rightarrow$ ^{6}He$+\pi^-$ weak decay. The production rate of $^{6}_{\Lambda}$H undergoing this two-body π^- decay has been found to be $(2.9 \pm 2.0) \cdot 10^{-6}/K^-_{\rm stop}$.

Its binding energy has been evaluated to be $B_\Lambda(^{6}_{\Lambda}{\rm H}) = (4.0 \pm 1.1)$ MeV with respect to ^{5}H + Λ, jointly from production and decay. A systematic difference of (0.98 ± 0.74) MeV between B_Λ values derived separately from decay and from production has been tentatively assigned to the $^{6}_{\Lambda}$H $0^+_{\rm g.s.} \rightarrow 1^+$ excitation.

A similar investigation has been carried out for the neutron-rich hypernucleus $^{9}_{\Lambda}$He studying the $K^-_{\rm stop}$ + ^{9}Be $\rightarrow$ $^{9}_{\Lambda}$He + π^+ reaction in coincidence with the $^{9}_{\Lambda}$He $\rightarrow$ ^{9}Li + π^- weak decay; an upper limit for the production rate of $^{9}_{\Lambda}$He undergoing the two-body π^- decay has been found to be $4.2 \cdot 10^{-6}/{\rm K}^-_{stop}$ (90% C.L.).

a e-mail: botta@to.infn.it
b deceased

1 Introduction

The rôle of the Λ hyperon in stabilizing nuclear cores was pointed out in the early '60 by Dalitz and Levi Setti [1] discussing the existence of light hypernuclei with large neutron excess. This feature is demonstrated by the observation of ${}^{6}_{\Lambda}$He, ${}^{7}_{\Lambda}$Be, ${}^{8}_{\Lambda}$He, ${}^{9}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B hypernuclei in emulsion experiments [2]. No unstable-core hydrogen Λ hypernuclei have been found so far, although the existence of the lightest possible one ${}^{6}_{\Lambda}$H was predicted in [1] and subsequently reinforced in estimates by Majling [3]. The neutral-baryon excess in ${}^{6}_{\Lambda}$H, in particular, would be $(N + Y)/Z = 5$, with $Y = 1$ for a Λ hyperon, or $N/Z = 4$, larger than the maximal value in light nuclei, $N/Z = 3$ for ^{8}He [4]. Neutron-rich light hypernuclei could thus go beyond the neutron drip line for ordinary nuclear systems. The study of ${}^{6}_{\Lambda}$H and of heavier neutron-rich hypernuclei could place valuable constraints on the size of coherent $\Lambda N - \Sigma N$ mixing in dense strange neutron-rich matter [5] with immediate impact on the stiffness/softness of the equation of state for hyperons in neutron-star matter [6].

Neutron rich hypernuclei could be produced by the two-body double charge-exchange reactions:

$$K^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}(Z-2) + \pi^+, \tag{1}$$

induced on nuclear targets by stopped or in flight K^- mesons, and

$$\pi^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}(Z-2) + K^+ \tag{2}$$

with π^- mesons in flight ($p_{\pi^-} > 0.89$ GeV/c).

These reactions can be described as two-step processes on two different protons of the same nucleus, which convert them first into a neutron and then into a Λ, with the additional condition that the final nuclear system is bound. Another mechanism could be a single-step double charge exchange $m_i^- p \rightarrow \Sigma^- m_f^+$ (where m stands for meson) feeding the Σ component coherently admixed into the final Λ hypernuclear state. The two-step processes are expected to occur at a rate $\leq 10^{-2}$ smaller [7] than the production of normal Λ hypernuclei by means of the corresponding single-step two-body reactions (K^-, π^-) and (π^+, K^+).

The first experimental attempt to produce neutron-rich hypernuclei was carried out at KEK [8] with the reaction (1) with K^- at rest. Upper limits were obtained for the production of ${}^{9}_{\Lambda}$He, ${}^{12}_{\Lambda}$Be and ${}^{16}_{\Lambda}$C hypernuclei (on ^{9}Be, ^{12}C and ^{16}O targets respectively) in the range of $(0.6 - 2.0) \cdot 10^{-4}/K^-_{\text{stop}}$. Another KEK experiment [9] reported the production of ${}^{10}_{\Lambda}$Li in the (π^-, K^+) reaction on a ^{10}B target using a 1.2 GeV/c π^- beam, with a cross section of 11.3 ± 1.9 nb/sr in the Λ-bound region.

A further attempt to observe neutron-rich hypernuclei by means of the reaction (1) with K^- at rest, was made at the DAΦNE collider at LNF by the FINUDA experiment [10], on ^{6}Li and ^{7}Li targets. From the analysis of a partial data sample, upper limits were evaluated for Λ hypernuclear production: $R_{\pi^+}({}^{6}_{\Lambda}\text{H}) < (2.5 \pm 0.4_{\text{stat}}{}^{+0.4}_{-0.1\text{syst}}) \cdot 10^{-5}/K^-_{\text{stop}}$, $R_{\pi^+}({}^{7}_{\Lambda}\text{H}) < (4.5 \pm 0.9_{\text{stat}}{}^{+0.4}_{-0.1\text{syst}}) \cdot 10^{-5}/K^-_{\text{stop}}$. In addition an upper limit was estimated for ${}^{12}_{\Lambda}$Be: $R_{\pi^+}({}^{12}_{\Lambda}\text{Be}) < (2.0 \pm 0.4_{\text{stat}}{}^{+0.3}_{-0.1\text{syst}}) \cdot 10^{-5}/K^-_{\text{stop}}$, which lowers by a factor ~ 3 the previous KEK determination [8].

Recently, analyzing the complete available data sample, the FINUDA experiment has reported an experimental evidence for the existence of ${}^{6}_{\Lambda}$H [11,12]. The increased statistics has been exploited to reduce the overwhelming background events in reaction (1) with K^- at rest by requiring a coincidence with π^- mesons from the two-body weak decay of the produced hypernucleus:

$$K^-_{\text{stop}} + {}^{6}\text{Li} \rightarrow {}^{6}_{\Lambda}\text{H} + \pi^+ \quad (p_{\pi^+} \sim 252 \text{ MeV/c}) \tag{3}$$

$${}^{6}_{\Lambda}\text{H} \rightarrow {}^{6}\text{He} + \pi^- \quad (p_{\pi^-} \sim 134 \text{ MeV/c}); \tag{4}$$

the same method has also been applied to the search of ${}^{9}_{\Lambda}$He produced on ^{9}Be targets. In this paper a description of the coincidence technique is given and results on production rates are discussed.

2 Evidence for ${}^{6}_{\Lambda}$H.

FINUDA was a hypernuclear physics experiment installed at one of the two interaction regions of the DAΦNE e^+e^- collider, the INFN-LNF $\Phi(1020)$-factory. A description of the experimental apparatus can be found in Ref. [12]; we only recall the experimental features relevant to the present analysis. For π^+ with momentum $\sim$ 250 MeV/c the resolution of the tracker, determined by means of the peak by monochromatic (236.5 MeV/c) μ^+ from $K_{\mu 2}$ decay, is $\sigma_p = (1.1 \pm 0.1)$ MeV/c [13] and the precision on the absolute momentum calibration is better than 0.12 MeV/c for the ^{6}Li targets. For π^- with momentum $\sim$ 130 MeV/c the resolution and absolute calibration are evaluated from the peak of the monochromatic (132.8 MeV/c) π^- coming from the two-body weak decay of the ${}^{4}_{\Lambda}$H hyperfragment [14]; a resolution $\sigma_p = (1.2 \pm 0.1)$ MeV/c and precision of 0.2 MeV/c were found.

Since the stopping time of ${}^{6}_{\Lambda}$H in metallic Li is shorter than its lifetime, both production (3) and decay (4) occur at rest; a straightforward algebra leads to the following expression for $T_{\rm sum} \equiv T(\pi^+) + T(\pi^-)$:

$$T_{\rm sum} = M(K^-) + M(p) - M(n) - 2M(\pi) - B({}^6\text{Li}) + B({}^6\text{He}) - T({}^6\text{He}) - T({}^{6}_{\Lambda}\text{H}), \qquad (5)$$

in which M stands for known masses, B for known nuclear binding energies, and T for kinetic energies. The value of $T_{\rm sum}$ varies merely by 50 keV upon varying $B_\Lambda({}^{6}_{\Lambda}\text{H})$ by 1 MeV, therefore negligibly with respect to the experimental energy resolution for a $\pi^\pm$ pair in coincidence, $\sigma_T = 1.28$ MeV. Evaluating the r.h.s. of Eq. (5) by assuming $B_\Lambda({}^{6}_{\Lambda}\text{H}) = 5$ MeV, from the average of 4.2 and 5.8 MeV predicted in Refs. [1,5], one obtains $T_{\rm sum} = 203 \pm 1.3$ MeV for ${}^{6}_{\Lambda}$H candidate events.

In the analysis events in the interval $T_{\rm sum} = 203 \pm 1$ MeV were considered, as a compromise between the contamination from background reactions discussed in more detail below, and the available statistics.

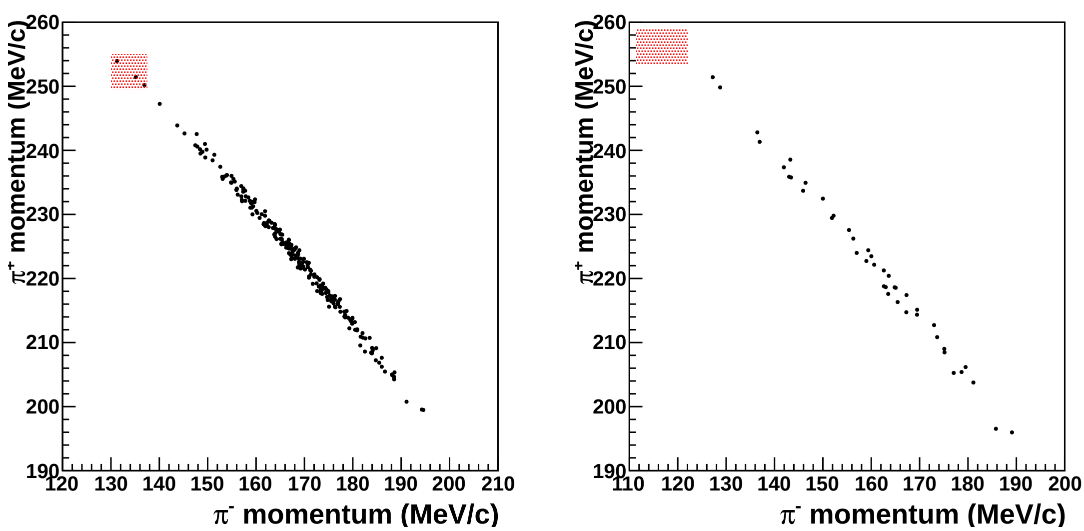

Fig. 1. Left: π^+ momentum vs π^- momentum for ^{6}Li target events with $T_{\rm sum} = 202 - 204$ MeV. The red rectangle consists of a subset of events with $p_{\pi^+} = 250 - 255$ MeV/c and $p_{\pi^-} = 130 - 137$ MeV/c. Right: π^+ momentum vs π^- momentum for ^{9}Be target events with $T_{\rm sum} = 194.5 - 197.5$ MeV. The red rectangle indicates the position of events with $p_{\pi^+} = 253.5 - 259$ MeV/c and $p_{\pi^-} = 114.5 - 122$ MeV/c.

Figure 1 (left) shows a 2-d plot in the (p_{π^-}, p_{π^+}) plane for coincidence events selected in the band $T_{\rm sum} = 202 - 204$ MeV. The distribution drops above $p_{\pi^+} \simeq 245$ MeV/c and below $p_{\pi^-} \simeq 145$ MeV/c. This is close to the region where ${}^{6}_{\Lambda}$H events are expected. To search for particle-stable ${}^{6}_{\Lambda}$H events below its $({}^{4}_{\Lambda}\text{H} + 2n)$ lowest threshold (see Fig.2 left for a scheme of particle emission thresholds), using the two-body kinematics of Eqs. (3) and (4), a further requirement of $p_{\pi^+} > 251.9$ MeV/c and $p_{\pi^-} < 135.6$

Table 1. Summed kinetic energy $T_{\rm sum} = T(\pi^+) + T(\pi^-)$, pion momenta $p_{\pi^\pm}$, and mass values inferred for the three ${}^6_\Lambda$H candidate events from production (3) and decay (4). The mean mass value is $M({}^6_\Lambda\mathrm{H})$ = 5801.4 ± 1.1 MeV, see text.

$T_{\rm sum}$ (MeV)	p_{π^+} (MeV/c)	p_{π^-} (MeV/c)	$M({}^6_\Lambda\mathrm{H})_{\rm prod.}$ (MeV)	$M({}^6_\Lambda\mathrm{H})_{\rm decay}$ (MeV)
202.6±1.3	251.3±1.1	135.1±1.2	5802.33±0.96	5801.41±0.84
202.7±1.3	250.1±1.1	136.9±1.2	5803.45±0.96	5802.73±0.84
202.1±1.3	253.8±1.1	131.2±1.2	5799.97±0.96	5798.66±0.84

MeV/c is necessary. The ranges p_{π^+} = (250 − 255) MeV/c and p_{π^-} = (130 − 137) MeV/c were selected, covering a ${}^6_\Lambda$H mass range from the (Λ + ^{3}H + 2n) threshold, about 2 MeV in the ${}^6_\Lambda$H continuum (see Fig. 2 left), down to a ${}^6_\Lambda$H bound somewhat stronger than predicted by Akaishi *et al.* [5]. This does not completely exclude possible contributions from the production and decay of (${}^4_\Lambda$H + 2n): a complete discussion of the analysis technique can be found in [11, 12].

Out of a total number of $\sim 2.7 \cdot 10^7$ K^- stopped in the ^{6}Li targets, we found three events that satisfy the final requirements, as shown within the red rectangle in Fig.1 left. Different choices of $T_{\rm sum}$ interval widths (2 − 6 MeV) and position (center in 202 − 204 MeV), and of $p_{\pi^\pm}$ interval widths (5 − 10 and 8 − 15 MeV/c respectively) with fixed limits at 250 and 137 MeV/c respectively to exclude the unbound region, do not affect the population of the selected region. This rules out systematic errors associated with the present analysis selection.

The three ${}^6_\Lambda$H candidate events are listed in Table 1 together with nuclear mass values derived separately from production (3) and from decay (4); the errors reported are evaluated directly from the tracker resolution for π^+ and π^- discussed before. These mass values yield a mean value $M({}^6_\Lambda\mathrm{H})$ = 5801.4 ± 1.1 MeV, jointly from production and decay where the error is given by the spread of the average mass values for the three events.

Furthermore, we note from Table 1 that the mass values associated with production are systematically higher than those evaluated from the decay, by 0.98 ± 0.74 MeV. These mass differences could be connected to the excitation spectrum of ${}^6_\Lambda$H.

2.1 Background estimate, production rate and discussion

A complete simulation of $K^-_{\rm stop}$ absorption reactions on single nucleons was performed, as well as on correlated few-nucleon clusters, that lead to the formation and decay of Λ and Σ hyperons. Full details can be found in [12], here it is sufficient to focus on one chain of reactions likely to produce $\pi^\pm$ coincidences overlapping with those selected to satisfy ${}^6_\Lambda$H production (3) and decay (4): Σ^+ production

$$K^-_{\rm stop} + {}^6\mathrm{Li} \rightarrow \Sigma^+ + {}^4\mathrm{He} + n + \pi^-, \tag{6}$$

where $p_{\pi^-} \leq 190$ MeV/c, followed by Σ^+ decay in flight

$$\Sigma^+ \rightarrow n + \pi^+ \quad [p_{\pi^+} \leq 282 \text{ MeV/c}]. \tag{7}$$

The Σ^+ production was treated in the quasi–free approach, following the analysis of the FINUDA experiment observing $\Sigma^\pm\pi^\mp$ pairs [15]; in the signal region a small contribution of 0.16 ± 0.07 expected events was evaluated. The reaction chain of ${}^4_\Lambda$H hyperfragment production and two body decay has been estimated to deliver a negligible background of 0.04 ± 0.01 expected events. All other reaction chains that could produce $\pi^\pm$ coincidences within the described selection ranges were ruled out by the selections applied. Turning to potential instrumental backgrounds, we note that these could result from fake tracks, filtered because of reconstruction errors. To this end we considered, with the same cuts, events coming from different nuclear targets used in the same runs (^{7}Li, ^{9}Be, ^{13}C, ^{16}O). We found one event coming from ^{9}Be and accordingly evaluate as 0.27 ± 0.27 the expected fake events from ^{6}Li, due to instrumental background.

A total background of 0.43 ± 0.28 expected events was evaluated. Thus, using Poisson distribution, the three $^6_\Lambda$H-assigned events do not arise from background to a confidence level of 99%. The statistical significance of the result is S=7.1 considering only the physical background, S=3.9 considering both physical and instrumental backgrounds.

Given the above background estimates, plus efficiency, target purity and cut estimates, it is possible to evaluate the product $R(\pi^+) \cdot \mathrm{BR}(\pi^-)$, where $R(\pi^+)$ is the $^6_\Lambda$H production rate per K^-_{stop} in reaction (3) and $\mathrm{BR}(\pi^-)$ the branching ratio for the two-body π^- decay (4):

$$R(\pi^+) \cdot \mathrm{BR}(\pi^-) = (2.9 \pm 2.0) \cdot 10^{-6}/K^-_{\mathrm{stop}}. \tag{8}$$

Assuming $\mathrm{BR}(\pi^-) = 49\%$, as for the analogous $^4_\Lambda\mathrm{H} \rightarrow {}^4\mathrm{He} + \pi^-$ decay [14], we find $R(\pi^+) = (5.9 \pm 4.0) \cdot 10^{-6}/K^-_{\mathrm{stop}}$, fully consistent with the previous FINUDA upper limit [10]. This production rate $R(\pi^+)$ is two to three orders of magnitude smaller than summed Λ-bound production rates $R(\pi^-)$ of normal light Λ hypernuclei in the (K^-_{stop}, π^-) reaction [13].

Table 1 yields a mean value $B_\Lambda(^6_\Lambda\mathrm{H}) = 4.0 \pm 1.1$ MeV with respect to $^5\mathrm{H} + \Lambda$, as shown in Fig. 2, in good agreement with the estimate 4.2 MeV [1] but considerably short of Akaishi's prediction $B^{\mathrm{th}}_\Lambda(^6_\Lambda\mathrm{H}) = 5.8$ MeV [5]. This indicates that coherent $\Lambda N - \Sigma N$ mixing in the s-shell hypernucleus $^4_\Lambda$H [16] becomes rather ineffective for the excess p shell neutrons in $^6_\Lambda$H.

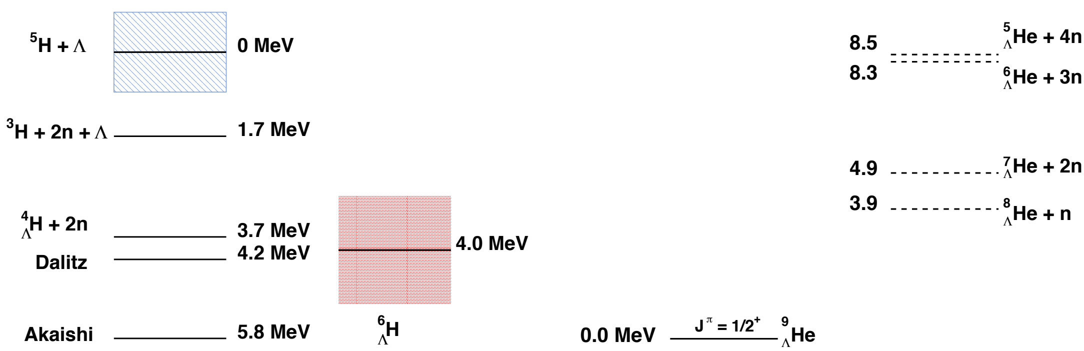

Fig. 2. Left: $^6_\Lambda$H binding energy with respect to $^5\mathrm{H} + \Lambda$ from three candidate events, as related to several particle emission thresholds and theoretical predictions. Right: $^9_\Lambda$He neutron emission thresholds with respect to the g.s.. The two schemes are not in scale.

The three events that give evidence for a particle-stable $^6_\Lambda$H can also give additional information on its excitation spectrum. It is expected to consist of a 0^+ g.s. and 1^+ excited state as in $^4_\Lambda$H (1.04 MeV), and a 2^+ excited state as for the p-shell dineutron system in ^{6}He (1.80 MeV). In fact, it is $^6_\Lambda\mathrm{H}(1^+)$ that is likely to be produced in reaction (3) simply because Pauli spin is conserved in production at rest, and the Pauli spin of ^{6}Li is $S = 1$ to better than 98%. The weak decay (4), however, occurs from $^6_\Lambda\mathrm{H}(0^+)$ g.s. since the (unseen) γ transition $1^+ \rightarrow 0^+$ is about three orders of magnitude faster than weak decay. Indeed, the production vs decay mass difference 0.98 ± 0.74 MeV extracted from the three $^6_\Lambda$H events listed in Table 1 is comparable to the underlying 1.04 MeV 1^+ excitation in $^4_\Lambda$H. In this case the B_Λ value for the g.s. would be larger $B_\Lambda(^6_\Lambda\mathrm{H}_{\mathrm{g.s.}}) = 4.5 \pm 1.2$ MeV. This scenario requires further experimental as well as theoretical inquiries.

3 Search for $^9_\Lambda$He

The neutron-rich hypernucleus $^9_\Lambda$He is one of the exotic Λ-hypernuclear species considered decades ago in [1] and by Majling [3] who estimated $B_\Lambda(^9_\Lambda\mathrm{He}) = 8.5$ MeV. Fig. 2 on the right shows the $^9_\Lambda$He g.s. level, indicated with 0.0 MeV energy, together with neutron emission thresholds below the 8.5 MeV Λ emission threshold.

Since ^{9}Be targets were used in the same data taking of FINUDA in which $^{6}_{\Lambda}$H was produced on ^{6}Li targets, with a similar number of stopped K^-, the possibility was examined whether the method applied to the successful search for $^{6}_{\Lambda}$H could be extended to the case of $^{9}_{\Lambda}$He. $^{9}_{\Lambda}$He could be produced in the two-body reaction:

$$K^-_{\rm stop} + {}^{9}{\rm Be} \rightarrow {}^{9}_{\Lambda}{\rm He} + \pi^+. \tag{9}$$

Assuming $B_\Lambda({}^{9}_{\Lambda}{\rm He}) = 8.5$ MeV, it is straightforward to evaluate the momentum $p_{\pi^+} = 257.5$ MeV/c for a π^+ meson emitted in (9). Since ^{9}Li g.s. is particle stable [17], admitting thus a two-body weak decay:

$${}^{9}_{\Lambda}{\rm He}_{\rm g.s.} \rightarrow {}^{9}{\rm Li}_{\rm g.s.} + \pi^- \tag{10}$$

producing a π^- meson with $p_{\pi^-} = 116.9$ MeV/c, the coincidence method could indeed be applied. Observing that, also in this case, formation (9) and decay reaction (10) occur at rest, since the stopping time of $^{9}_{\Lambda}$He in the material (Be) is shorter than its lifetime (about 260 ps, the free Λ lifetime), from momentum and energy conservation it is immediate to derive an equation analogous to (5):

$$T_{\rm sum} = M(K^-) + M(p) - M(n) - 2M(\pi) - B({}^{9}{\rm Be}) + B({}^{9}{\rm Li}) - T({}^{9}{\rm Li}) - T({}^{9}_{\Lambda}{\rm He}) \tag{11}$$

in which, again, M stands for known masses, B for known nuclear binding energies, and T for kinetic energies. The value of $T_{\rm sum}$ varies by 10 keV upon varying $B_\Lambda({}^{6}_{\Lambda}{\rm H})$ by 1 MeV, negligible with respect to the experimental energy resolution discussed before. By considering a value of $B_\Lambda({}^{9}_{\Lambda}{\rm He}) = 8.5$ MeV [3], $T_{\rm sum} = 195.8 \pm 1.3$ MeV.

In this case, for the (π^+, π^-) coincidence only events for which $T_{\rm sum}$ assumed values in the range (194.5 – 197.5) MeV were considered. The two-dimensional plot of these selected events is shown in Fig. 1 right. Events associated with the formation of $^{9}_{\Lambda}$He with values of $B_\Lambda({}^{9}_{\Lambda}{\rm He})$ varying between 5 and 10 MeV should fall in the red rectangle in the figure, corresponding to $p_{\pi^+} = (253.5 - 259)$ MeV/c and $p_{\pi^-} = (114.5 - 122)$ MeV/c. From Fig. 2 it is possible to see that a binding energy of 5 MeV is about 0.5 MeV below the lowest neutron emission threshold expected for $^{9}_{\Lambda}$He. There are clearly no events satisfying the conditions required by the formation and decay of $^{9}_{\Lambda}$He with $B_\Lambda({}^{9}_{\Lambda}{\rm He}) \geq 5$ MeV.

It was thus possible to derive an upper limit for $^{9}_{\Lambda}$He production rate $R \cdot {\rm BR}(\pi^-)$, where R is $^{9}_{\Lambda}$He production rate per stopped K^- in reaction (9) and ${\rm BR}(\pi^-)$ is the branching ratio (BR) for $^{9}_{\Lambda}$He two-body weak decay (10). Considering a 90% confidence level (C.L.), plus efficiency and cut estimates it was obtained:

$$R \cdot {\rm BR}(\pi^-) \leq \frac{N}{\epsilon(\pi^+)\ \epsilon(\pi^-)\ K^-_{\rm stop}({}^{9}{\rm Be})} < (2.3 \pm 1.9) \cdot 10^{-6}/K^-_{\rm stop} \rightarrow 4.2 \cdot 10^{-6}/K^-_{\rm stop}. \tag{12}$$

If for $BR(\pi^-)$ the value of 0.323 ± 0.062 is assumed, which is the experimental one for the mesonic weak decay of $^{5}_{\Lambda}$He [18], an upper limit is obtained for R of $(2.3 + 1.9)/0.323 \cdot 10^{-6}/K^-_{\rm stop} = 1.3 \cdot 10^{-5}/K^-_{\rm stop}$ (at 90% C.L.), improving by over an order of magnitude the previous upper limit set in KEK experiment [8]. The above assumption is based on the hypothesis that the mesonic weak decay of $^{9}_{\Lambda}$He is dominated by the substructure of hadrons in the s-shell ($^{5}_{\Lambda}$He) without strong influence from the four p-shell neutrons. A similar assumption was done for the evaluation of the ${\rm BR}(\pi^-)$ for $^{6}_{\Lambda}$H [11, 12].

4 Conclusions

FINUDA has presented the first evidence for heavy hyper-hydrogen $^{6}_{\Lambda}$H, based on detecting three events shown to be clear of instrumental and/or physical backgrounds. The derived binding energy of $^{6}_{\Lambda}$H limits the strength of the coherent $\Lambda N - \Sigma N$ mixing effect predicted in neutron-rich strange matter [5], together with the conjectured $0^+ - 1^+$ doublet splitting. FINUDA has also derived an upper limit for the production of the $^{9}_{\Lambda}$He hypernucleus, based on the same method of detecting a π^- weak decay in coincidence. A search of $^{6}_{\Lambda}$H and $^{9}_{\Lambda}$He in the (π^-, K^+) reaction at 1.2 GeV/c on ^{6}Li and ^{9}Be, respectively, is scheduled in the near future at J-PARC.

References

1. R.H. Dalitz and R. Levi-Setti, Nuovo Cimento **30** (1963) 489.
2. M. Jurić *et al.*, Nucl. Phys. **B 52** (1973) 1.
3. L. Majling, Nucl. Phys. **A 585** (1995) 211c.
4. D.R. Tilley *et al.*, Nucl. Phys. **A 745** (2004) 155.
5. Y. Akaishi and T. Yamazaki, in **Frascati Physics Series XVI** (1999) 59; S. Shinmura, K.S. Myint, T. Harada, and Y. Akaishi, J. Phys. G **28** (2002) L1; for a recent review, see Y. Akaishi and K.S. Myint, AIP Conf. Proc. **1011** (2008) 277, Y. Akaishi, Prog. Theor. Phys. Suppl. **186** (2010) 378, and references therein.
6. J. Schaffner-Bielich, Nucl. Phys. **A 804** (2008) 309, Nucl. Phys. **A 835** (2010) 279.
7. R.E. Chrien, C.B. Dover, A. Gal, Czech. J. Phys. **42** (1992) 1089.
8. K. Kubota *et al.*, Nucl. Phys. **A 602** (1996) 327.
9. P.K. Saha *et al.*, Phys. Rev. Lett. **94** (2005) 052502.
10. M. Agnello *et al.*, Phys. Lett. **B 640** (2006) 145.
11. M. Agnello *et al.*, Phys. Rev. Lett. **108** (2012) 042501.
12. M. Agnello *et al.*, Nucl. Phys. **A 881** (2012) 269.
13. M. Agnello *et al.*, Phys. Lett. **B 698** (2011) 219.
14. H. Tamura *et al.*, Phys. Rev. **C 40** (1989) R479.
15. M. Agnello *et al.*, Phys. Lett. **B 704** (2011) 474.
16. Y. Akaishi, T. Harada, S. Shinmura, and K.S. Myint, Phys. Rev. Lett. **84** (2000) 3539.
17. see http://www.nndc.bnl.gov/ for nuclear data compilation.
18. M. Agnello *et al.*, Phys. Lett. **B 681** (2009) 139.