First experimental evidence for heavy hyperhydrogen $^6\Lambda^1$H by the FINUDA experiment at DAΦNE
First experimental evidence for heavy hyperhydrogen $^{6}_Λ$H by the FINUDA experiment at DAΦNE

Alessandro Feliciello
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, I-10125 Torino (Italy)
E-mail: Alessandro.Feliciello@to.infn.it

Abstract. The FINUDA experiment, carried out at the Frascati $Φ$-factory DAΦNE, allowed to find the first experimental evidence for the existence of the neutron-rich hypernucleus $^{6}_Λ$H by measuring in coincidence ($π^+, π^−$) pairs from the $K^-_{stop}$ + $^6$Li → $^6_Λ$H + $π^+$ production reaction, followed by the $^6_Λ$H → $^6$He + $π^−$ mesonic weak decay. The production rate of $^6_Λ$H undergoing such a two-body $π^−$ decay turned out to be $(2.9 \pm 2.0) \times 10^{-6}/K^-_{stop}$. A binding energy value $B_Λ(^6_Λ$H) = $(4.0 \pm 1.1)$ MeV was evaluated with respect to the $(^5$H + Λ) threshold by combining the information from both production and decay processes. A systematic difference of $(0.98 \pm 0.74)$ MeV observed between $B_Λ$ values when derived separately from $^6_Λ$H formation and from its decay was tentatively assigned to the $^6_Λ$H $^+_2$g.s. → $^1^+_+$ excitation.

1. Introduction

A neutron-rich Λ-hypernucleus is a bound strange $^1$ nuclear system with an unbalanced number of constituent neutrons or, in other words, with an unusually high neutron to proton ratio [1]. The search for such systems is legitimated by the experimental observation of the so-called glue-like role that the Λ hyperon manifests when it is embedded in a nucleus [2]. This property is essentially due to the attractive nature of the $ΛN$ interaction and to the fact that the Pauli principle is not effective for a single strange particle inside a nucleus. Unstable nuclear systems, like for instance $^8$Be, become then particle stable thanks to the critical contribution to the overall binding energy carried by the Λ. This effect is particularly evident for nuclei close to the proton- and neutron-drip lines, thus potentially expanding the boundary of the nuclear stability valley.

The motivations for trying to observe and for studying neutron-rich Λ-hypernuclei span over a wide spectrum. The discovery of these exotic systems could open very interesting scenarios as far as the investigation of few-body nuclear systems and of $ΛN$ interactions (both strong and weak) in a low density nuclear medium are concerned. This environment is then best suited to put in evidence the effects of the three-body forces involving hyperons ($ΛNN$) which are believed to reduce the stiffness of the nuclear matter equation of state (EoS) in neutron stars [3, 4]. In this respect, a precise knowledge of the light neutron-rich Λ-hypernuclei energy level structure could imply far-reaching consequences on strange dense stellar matter properties. Indeed, by constraining the $ΛN$ potential it could be possible to make more reliable predictions about the internal structure of neutron stars and in particular about their mass maximum value [5]. However, the recent measurement of two neutron star masses with values of the order of two solar masses [6, 7] seriously questions the real presence of hyperons in the neutron star core.

$^1$ i.e. with an explicit strangeness content
composition [8]. A possible way to face with this “hyperon crisis” is an extension of the three-body forces definition, by including the additional $YYN$ and $YYY$ channels as well. This way it would be possible to provide enough repulsive strength at high density stellar matter, thus reducing the softening of the EoS and then justifying the observation of very massive neutron stars.

When focusing the attention on the strict hypernuclear physics field, such studies offer the possibility to evaluate the strength of the coherent $\Lambda N - \Sigma N$ mixing and to check whether such mechanism is able to generate a sizeable attractive three-body $\Lambda N N$ force, making the strange nuclear system extremely deeply bound [9, 10, 11, 12, 13, 14].

The existence and the observability of neutron-rich $\Lambda$-hypermultiplets were first discussed by Dalitz and Levi Setti [1]. Afterwards, Majling endorsed this hypothesis and provided even more stringent predictions about their production rates [15].

Experimental evidences were actually found for $^3\Lambda$He, $^7\Lambda$Be, $^8\Lambda$Be, $^9\Lambda$B and $^{10}\Lambda$B $\Lambda$ hypernuclei in emulsion experiments [17]. However no unstable-core hydrogen $\Lambda$-hypernuclei were observed until very recently. $^3\Lambda$H is the simplest neutron-rich hypernucleus and, at the same time, it is the bound strange nuclear system with the largest possible neutral baryon excess. Actually it would be $(N + Y)/Z = 5$, with $Y = 1$ for a $\Lambda$ hyperon, or $N/Z = 4$, larger than the maximal value in light nuclei $N/Z = 3$ for $^8\Lambda$He [16]. In this case the stabilized core nucleus is $^5\Lambda$H.

The accelerator-aided neutron-rich $\Lambda$-hypernucleus production can be achieved by exploiting the two-body double charge-exchange reaction

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

induced on nuclear targets by $K^-$ meson both in flight and at rest, or

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

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

Both these reactions can be described as two-step processes involving two different protons of the same nucleus, in which they are sequentially transformed into a $\Lambda$ particle and a neutron (or vice versa), leading to a final bound strange nuclear system. Another possible mechanism could be a one-step double charge exchange $m^\Lambda - p \rightarrow \Sigma^- m^\Lambda_f$ (where $m^\Lambda$ stands for the initial $\pi^-/K^-$ meson and $m^\Lambda_f$ for the final $K^+/\pi^+$ one) feeding the $\Sigma$ component coherently admixed into the final $\Lambda$ hypernuclear state. The two-step processes (1) and (2) are expected to occur at a rate two orders of magnitude smaller [18] than the ones for “normal” $\Lambda$-hypernuclei production via the corresponding one-step two-body reactions ($K^-/\pi^-$ and ($\pi^+, K^+$).

The first experimental attempt to produce neutron-rich hypernuclei was carried out by exploiting the reaction (1) at KEK [19]. Upper limits were obtained for the production of $^9\Lambda$He, $^{12}\Lambda$Be and $^{16}\Lambda$C (on $^9$Be, $^{12}$C and $^{16}$O targets respectively), all lying in the $(0.6 - 2.0) \times 10^{-4} / K_{\text{stop}}$ range. A second KEK experiment (E521), reported the production of $^{10}\Lambda$Li in the ($\pi^-, K^+$) reaction on a $^{10}$B target using a 1.2 GeV/c $\pi^-$ beam, with a cross section of $(11.3 \pm 1.9) \text{ nb} / \text{sr}$, integrated over the whole $\Lambda$ bound region [20].

2. The FINUDA experiment

2.1. The apparatus and its performances

FINUDA was a complex magnetic spectrometer installed on the DAΦNE $e^+e^-$ collider, the Italian $\phi$ (1020)-factory put in operation at the INFN National Laboratories of Frascati, near Rome. It was carefully designed and specially dedicated to an extensive program of hypernuclear physics, mainly focused on spectroscopy of light $\Lambda$-hypernuclei and on systematic study of their decay modes. The apparatus was carefully modeled and optimized by means of a sophisticated
Table 1. Upper limits at a 90% C.L. for neutron-rich $\Lambda$-hypernuclei production rate $R_{\pi^+}$ per stopped $K^-$ for the $(K^-,\pi^+)$ reaction. (From [25]).

| target | $\Lambda$-hypernucleus | $R_{\pi^+} [\times 10^{-5}/K_{\text{stop}}]$ |
|---------|------------------------|------------------------------------------|
| $^6\text{Li}$ | $^6\Lambda$H | $\leq 2.5 \pm 0.4_{\text{stat}}^{+0.4}_{-0.1} \text{syst}$ |
| $^7\text{Li}$ | $^7\Lambda$H | $\leq 4.5 \pm 0.9_{\text{stat}}^{+0.4}_{-0.1} \text{syst}$ |
| $^{12}\text{C}$ | $^{12}\Lambda$Be | $\leq 2.0 \pm 0.4_{\text{stat}}^{+0.3}_{-0.1} \text{syst}$ |

simulation code, based on the GEANT3 software package [21]. This phase was driven by the constraints imposed by the DAΦNE accelerator peculiar footprint and by the requirement of fully exploiting both the $K^-$ source topology and the $K^-$ “beam” characteristics. The final outcome was a detector characterized by a complex architecture, whose description can be found in [22].

However, it is important to mention here at least the main spectrometer performances, relevant to the present analysis. For a ~250 MeV/c $\pi^+$ the tracker momentum resolution, measured by looking at the peak due to monochromatic 236.5 MeV/c $\mu^+$ from $K^-\pi^0$ decay, was $\sigma_p = (1.1 \pm 0.1)$ MeV/c [23]; this figure translated in a resolution on the kinetic energy $\sigma_T = 0.96$ MeV. The precision on the absolute momentum calibration was better than 0.12 MeV/c in the case of $^6\text{Li}$ targets, giving a systematic deviation on the kinetic energy $\sigma_{T,\text{syst}}(\pi^+) = 0.1$ MeV. For a ~130 MeV/c $\pi^-$ the momentum resolution and the absolute energy calibration were evaluated by measuring the peak due to monochromatic 132.8 MeV/c $\pi^-$ coming from the two-body mesonic weak decay of $^4\Lambda$H hyperfragments produced with a formation probability of $\sim 10^{-3}$–$10^{-2}$ per stopped $K^-$ [24]; in this case a resolution $\sigma_p = (1.2 \pm 0.1)$ MeV/c, giving $\sigma_T = 0.84$ MeV, and a precision of 0.2 MeV/c, giving a systematic deviation on the kinetic energy $\sigma_{T,\text{syst}}(\pi^-) = 0.14$ MeV, were achieved.

2.2. The $^6\Lambda$H search strategies

The FINUDA Collaboration pursued the objective of producing and of detecting $^6\Lambda$H, $^7\Lambda$H and $^{12}\Lambda$Be since the very beginning of its activity, by exploiting the unrivaled characteristics of the kaon source available at DAΦNE jointly to the excellent capabilities of the apparatus.

The strategy adopted in analyzing the first limited data sample (${\mathcal L}_{\text{int}} \sim 220 \text{ pb}^{-1}$) consisted in searching for discrete peaks in the region of interest in the momentum spectrum of $\pi^+$ emitted following the $K^-$ capture at rest on $^6\text{Li}$, $^7\text{Li}$ and $^{12}\text{C}$ targets. Because of the overwhelming background due to concurrent $K^-$ induced processes, it was possible to provide only upper limits at a 90% C.L., listed in table 1. In the case of $^{12}\Lambda$Be, the FINUDA determination lowered by a factor $\sim 3$ the aforementioned KEK results [19].

A second data taking campaign allowed to increase the statistics collected with $^6\text{Li}$ targets by a factor 5 (${\mathcal L}_{\text{int}} \sim 1156 \text{ pb}^{-1}$). However even in this case it was not possible to observe in the inclusive $\pi^+$ momentum spectrum clear peaks that could be unambiguously attributed to the two-body, double charge exchange reaction:

$$K^-_{\text{stop}} + ^6\text{Li} \rightarrow ^6\Lambda\text{H} + \pi^+ \quad (p_{\pi^+} \approx 252 \text{ MeV/c} \quad \text{when} \quad B_\Lambda \approx 5 \text{ MeV}).$$

Then, by exploiting the larger number of reconstructed events, a new analysis strategy was adopted with the aim of reducing the physical background. It consisted in looking at the $\pi^+$ momentum distribution by requiring in coincidence the $\pi^-$ coming from the $^6\Lambda$H mesonic decay:

$$^6\Lambda\text{H} \rightarrow ^6\text{He} + \pi^- \quad (130 \lesssim p_{\pi^-} \lesssim 140 \text{ MeV/c}).$$
Figure 1. π$^+$ momentum vs. π$^-$ momentum plot for $^6$Li target events with $202$ MeV $\leq T_{tot} \leq 204$ MeV (left panel) and with $200$ MeV $\leq T_{tot} \leq 206$ MeV (right panel). Red hatched areas correspond to event subsets with $250$ MeV/c $\leq p_{\pi^+} \leq 255$ MeV/c and $130$ MeV/c $\leq p_{\pi^-} \leq 137$ MeV/c, respectively. Blue hatched areas are the symmetric event subsets. (From [27]).

In order to identify the events due to the $^6\Lambda$H possible formation in a bound state, energy conservation was imposed to both reactions (3) and (4). Momentum conservation is automatically satisfied because both formation and decay processes occur at rest: (3) by definition and (4) because $^6\Lambda$H stopping time in the target is indeed shorter than its lifetime. It was then realized that, while both π$^-$ and π$^+$ momenta depend on the energy level in which the Λ-hypernucleus is formed, the sum of their kinetic energies ($T_{tot} = T_{\pi^+} + T_{\pi^-}$) is, to a first approximation, independent of it and equal to $203.0$ MeV [27]. By taking into account the tracker energy resolution, events with $T_{tot} = (203 \pm 1) \text{ MeV}$ and satisfying additional cuts on π$^+$ and π$^-$ momentum values ($250 \leq p_{\pi^+} \leq 255 \text{ MeV/c}$ and $130 \leq p_{\pi^-} \leq 137 \text{ MeV/c}$) were selected. These latter limits are equivalent to constrain the $B_{\Lambda}(^6\Lambda H)$ value in the plausible range from 2 to 6 MeV, that is from the $(\Lambda + ^3H + 2n)$ threshold (about 2 MeV in the $^6\Lambda H$ continuum) down to a $^6\Lambda H$ bound somewhat deeper than predicted in [9, 10, 11, 12, 13, 14].

Three events, out of the $27 \times 10^6$ ones due to $K^-$ stopped in the two $^6$Li targets, survived to the filtering procedure [26], described in detail in [27]. Figure 1 shows graphically the effect of the selection cuts. Alternative choices for $T_{tot}$ interval width ($2 - 6 \text{ MeV}$) and central value ($202 - 204 \text{ MeV}$) and for $p_{\pi^\pm}$ accepted ranges ($5 - 10$ and $8 - 15 \text{ MeV/c}$, respectively) with fixed limits at $250$ and $137 \text{ MeV/c}$, respectively, to exclude the unbound region, do not affect the population of the selected region (red areas in figure 1). For instance, no additional candidate events appear in the red areas upon extending the $T_{tot}$ window from $202 - 204$ MeV to $200 - 206$ as it is possible to see in the right panel of figure 1. On the contrary, a similar stability is not observed in the blue hatched areas, where on the top of selected events with the first set of cuts, six additional events appear. The $^6\Lambda H$ mass values evaluated for each event both from production (3) and decay (4) processes are listed in table 2; the quoted errors are evaluated directly from the tracker momentum resolution for π$^+$ and π$^-$ recalced in Sec. 2.1. Such nuclear
mass values yield a mean value $M(^9\Lambda\Lambda) = (5801.4 \pm 1.1)$ MeV where the error is essentially due to the spread of the average mass values for the three events. The inferred $^9\Lambda\Lambda$ binding energies $B_\Lambda = (4.0 \pm 1.1)$ MeV, with respect to the $(\Lambda + ^5\text{Li})$ threshold, and $B_\Lambda = (0.3 \pm 1.1)$ MeV, with respect to the lowest particle stable threshold $(^1\Lambda\Lambda + 2n)$, are in excellent agreement with the predictions of both [1] and [15]. On the contrary the first value is significantly lower than the outcome of the calculations described in [9, 10, 11, 12, 13, 14], where the coherent $\Lambda N'$-$\Sigma N'$ mixing effect is invoked in order to justify a considerable higher binding energy for $^9\Lambda\Lambda$. Then the present result seems to support the hypothesis of a reduced effectiveness of such a mechanism, in line with the output of some recent shell-model calculations [28].

The mass values obtained from production process (3) turned out to be systematically higher than those inferred from decay one (4) by $(0.98 \pm 0.74)$ MeV. A possible physical origin for such a difference, discussed in [26] and [27], could be related to the $^9\Lambda\Lambda$ excitation spectrum: the production could occur preferentially to an $\sim 1$ MeV $1^+$ excited state, then decaying through a fast $M1\gamma$-transition to the $0^+$ ground state of $^9\Lambda\Lambda$, which in turn undergoes the mesonic weak decay.

In order to provide a correct evaluation of the $^9\Lambda\Lambda$ production rate, a careful study of the possible background sources was performed. A complete simulation of $K_{\text{stop}}^-\Lambda\Lambda$ absorption reactions, both on single and on correlated few-nucleons clusters, leading to the formation and the decay of $\Lambda$ and $\Sigma$ hyperons was then carried out. The full description of this task can be found in [27]; here it is enough to focus on just one chain of reactions likely to produce $(\pi^+,\pi^-)$ pairs in coincidence overlapping with those selected to identify $^9\Lambda\Lambda$ formation (3) and decay (4) processes, namely $\Sigma^+$ production

$$K_{\text{stop}}^- + ^6\text{Li} \rightarrow \Sigma^+ + ^4\text{He} + n + \pi^- \quad (p_{\pi^-} \leq 190 \text{ MeV/c}),$$

followed by in-flight $\Sigma^+$ decay

$$\Sigma^+ \rightarrow n + \pi^+ \quad (p_{\pi^+} \leq 282 \text{ MeV/c}).$$

The $\Sigma^+$ production was treated in the quasi-free approach, according to the outcome of the previous FINUDA study of the $A(K_{\text{stop}}^-\Lambda\Lambda, \pi^+\Sigma^+)A'$ reaction on $p$-shell nuclei [29]; in the signal region a small contribution of $(0.16 \pm 0.07)$ expected background events was estimated. Another possible source of physical background, is the $^9\Lambda\Lambda$ hyperfragment production and its subsequent two-body decay. This contamination is strongly suppressed by the cut on $T_{\text{tot}}$, then the expected number of background events turned out to be as small as $(0.04 \pm 0.01)$. All other reaction chains that could produce $(\pi^+,\pi^-)$ pairs in coincidence, falling within the above described regions of interest, were filtered thanks to the applied selection cuts. As far as the instrumental backgrounds are concerned, they could mainly result from fake tracks, included in the data

**Table 2.** Pion momenta $p_{\pi\pm}$ and mass values for the three $^9\Lambda\Lambda$ candidate events. Masses are evaluated both from production (3) and decay (4) reactions. In the last two columns the mass mean value and the difference between production and decay masses are reported. (From [27]).

| $p_{\pi^+}$ | $p_{\pi^-}$ | $M(^9\Lambda\Lambda)$ prod. | $M(^9\Lambda\Lambda)$ decay | $M(^9\Lambda\Lambda)$ mean | $\Delta M(^9\Lambda\Lambda)$ |
|---|---|---|---|---|---|
| [MeV/c] | [MeV/c] | [MeV] | [MeV] | [MeV] | [MeV] |
| 251.3 ± 1.1 | 135.1 ± 1.2 | 5802.33 ± 0.96 | 5801.41 ± 0.84 | 5801.87 ± 0.96 | 0.92 ± 1.28 |
| 250.1 ± 1.1 | 136.9 ± 1.2 | 5803.45 ± 0.96 | 5802.73 ± 0.84 | 5803.09 ± 0.96 | 0.72 ± 1.28 |
| 253.8 ± 1.1 | 131.2 ± 1.2 | 5799.97 ± 0.96 | 5798.66 ± 0.84 | 5798.32 ± 0.96 | 1.31 ± 1.28 |
The FINUDA Collaboration presented the first experimental evidence for heavy hyper-hydrogen \(^6\Lambda\)H. Conclusions analogous KEK measurement on \(^6\Lambda\)H-target was, was filtered. Accordingly, the estimated number of fake events from the \(^6\Lambda\)H-target was \((0.27 \pm 0.27)\). The total number of background events was then \((0.43 \pm 0.28)\). Thus, by using Poisson statistics, it was possible to conclude that the three \(^6\Lambda\)H-assigned events do not arise from background at a 99% confidence level, the statistical significance of the result being \(S = 3.9\). By taking into account the above considerations, the apparatus reconstruction efficiency for \(\pi^-\), the target purity and the cut effectiveness the product \(R_{\pi^+} \cdot BR(\pi^-)\), where \(R_{\pi^+}\) is the \(^6\Lambda\)H-production rate per \(K_{\pi^+}^-\) in reaction (3) and \(BR(\pi^-)\) is the unknown branching ratio for the two-body mesonic \(\pi^-\) decay (4), turned out to be:

\[
R_{\pi^+}(^6\Lambda\)H\) \cdot BR(\pi^-) = (2.9 \pm 2.0) \times 10^{-6}/K^-_{\pi^+}.
\]

Finally, by assuming \(BR(\pi^-) = 49\%\), in analogy to the experimental result for \(^4\Lambda\)He \(\rightarrow^4\) He + \(\pi^-\) decay [24], \(R_{\pi^+} = (5.9 \pm 4.0) \times 10^{-6}/K^-_{\pi^+}\), a value fully consistent with the previous published result [25] and two to three orders of magnitude smaller than summed \(\Lambda\)-bound production rates \(R_{\pi^-}\) of "normal" light \(\Lambda\)-hypernuclei in the \((K^-_{\pi^+},\pi^-)\) reaction [23].

3. Discussion
The FINUDA claim is now triggering a lively debate on the \(^6\Lambda\)H existence and its structure both in the theoretical physicist community and in the experimental physicist one. Very recently, Hiyama et al. computed the \(^6\Lambda\)H binding energy by exploiting a four-body-cluster-model [30]. According to these calculations, which are able to reproduce the \(^6\Lambda\)H properties, the \(\Lambda\) separation energy amounts to \(B_\Lambda = 2.47\) MeV only. This means that both \(0^+\) and \(1^+\) states are unbound, in contrast to the FINUDA experimental evidence. Gal and Millener performed a shell-model calculation in order to predict in turn the binding energy for the system made by a \(^4\Lambda\)He core plus a pair of neutrons [31]. In this case the obtained binding energy value was \(B_\Lambda = (3.83 \pm 0.08 \pm 0.22)\) MeV, thus leaving room for an alternative interpretation of the FINUDA observation. They suggested that the \(1^+\) excited state could be unbound but characterized by a particle decay width extremely small and comparable with the one of the aforementioned M1 \(\gamma\)-transition to the \(0^+\) ground state. Such a hypothesis could be justified on the basis of a kinematical and dynamical suppression of the two neutron emission from the \(1^+\) state.

From the experimental point of view, it is clear that the \(^6\Lambda\)H discovery must be confirmed in an independent way and with much higher statistical significance. In this perspective, the E10 experiment was proposed and approved to run on the K1.8 beam line at the Japan Proton Accelerator Research Complex (J-PARC). It has been specifically designed to search for neutron-rich \(\Lambda\)-hypernuclei, namely \(^6\Lambda\)H and \(^6\Lambda\)He, and it could be considered the natural extension of the already mentioned KEK E521 one [20]. Actually, the neutron-rich \(\Lambda\)-hypernucleus production reaction exploited is the \((\pi^-,K^+)\) at 1.2 GeV/c. The E10 Collaboration took data in December 2012 and January 2013 with a \(^6\)Li target. The careful analysis of the measured missing mass spectrum found no significant indication for \(^6\Lambda\)H existence, neither below nor above the \((^6\Lambda\)H + 2n) particle decay threshold [32]. On the basis of three observed events in the region of interest, an upper limit for the production cross section of a bound \(^6\Lambda\)H hypernucleus was estimated to be \(1.2\) nb/sr at a 90% C.L., a value one order of magnitude lower that the one reported in the analogous KEK measurement on \(^{10}\)B target [20].

4. Conclusions
The FINUDA Collaboration presented the first experimental evidence for heavy hyper-hydrogen \(^6\Lambda\)H, based on the observation of three events, shown to be free from any instrumental
and/or physical backgrounds. The derived $^6\Lambda H$ binding energy value drastically downsizes the strength of the coherent $\Lambda N \to \Sigma N$ mixing effect predicted for neutron-rich strange matter [9, 10, 11, 12, 13, 14], together with the conjectured $0^- - 1^+$ doublet splitting.

However, the recent search for $^6\Lambda H$ performed by the E10 Collaboration at J-PARC did not confirm this observation [32]. Further measurements are then required in order to confirm whether $^6\Lambda H$ really exists. An important effort should be put in place on theoretical ground as well, to restore order among the different calculations and, possibly, to reconcile experimental evidence and theoretical prediction.

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