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First observation of ${}^{6}_{\Lambda}$H

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The FINUDA experiment has observed for the first time the hyper superheavy hydrogen ${}^{6}_{\Lambda}$H by means of the (K^{-}_{stop}, π^{+}) reaction on ^{6}Li. Preliminary results are presented concerning the binding energy of this exotic nuclear system and its production rate.

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1. Introduction

The so called 'glue-like' rôle of the Λ-hyperon in stabilizing nuclear cores has been suggested from the beginning of the Hypernuclear Physics, following the observation of Hypernuclei with large N/Z values, like $^{6}_{\Lambda}$He, $^{7}_{\Lambda}$He, $^{8}_{\Lambda}$He, $^{9}_{\Lambda}$Li in emulsion experiments; a recent review on this item is given in [1]. The possible existence of bound Λ-Hypernuclei with a very large neutron excess was first pointed out by Dalitz and Levi Setti [2] ten years after the discovery of Hypernuclei; the argument was that the Λ hyperon could act as a glue on systems of very few nucleons, otherwise unbound, and consequently neutron rich Λ-hypernuclei could go beyond the neutron stability drip line for ordinary nuclei. For $^{6}_{\Lambda}$H a binding energy of 4.2 MeV from the Λ+^{5}H unbound system mass was evaluated.

In 1995 Majling [3] reconsidered the item of the existence of neutron-rich Λ hypernuclei; in particular, for systems as light as $^{6}_{\Lambda}$H and $^{7}_{\Lambda}$H, he evaluated binding energies similar to those of normal Λ-hypernuclei in the same mass number range and production rates $\leq 10^{-5}$/K^{-}_{stop} for the (K^{-}_{stop}, π^{+}) production reaction, less than two orders of magnitude lower than that of normal Λ hypernuclei through the (K^{-}_{stop}, π^{-}) reaction.

Later, Akaishi and collaborators [4] evaluated the binding energy of the $^{6}_{\Lambda}$H system by introducing an additional binding contribution due to the three body ΛNN force resulting from the coherent part of the ΛN-ΣN coupling. A recent development of the calculation is given in [5].

From the experimental side, upper limits for the production of $^{9}_{\Lambda}$He, $^{12}_{\Lambda}$Be and $^{16}_{\Lambda}$C have been obtained [6] exploiting the (K^{-}_{stop}, π^{+}) reaction, while the production of $^{10}_{\Lambda}$Li has been reported [7] analyzing the (π^{-}, K^{+}) reaction in flight. The most recent attempt to observe neutron rich Λ-hypernuclei through the (K^{-}_{stop}, π^{+}) reaction was performed by the FINUDA experiment [8] on ^{6}Li, ^{7}Li and ^{12}C targets; upper limits were assessed for the production rates of $^{6}_{\Lambda}$H ($(2.5 \pm 0.4_{stat}\ {}^{+0.4}_{-0.1syst}) \cdot 10^{-5}$/$K^{-}_{stop}$, $^{7}_{\Lambda}$H ($4.5 \pm 0.9_{stat}{}^{+0.4}_{-0.1syst}) \cdot 10^{-5}$/$K^{-}_{stop}$ and $^{12}_{\Lambda}$Be ($2.0 \pm 0.4_{stat}\ {}^{+0.3}_{-0.1syst}) \cdot 10^{-5}$/$K^{-}_{stop}$.

2. Experimental and analysis technique

FINUDA [9] was an experiment installed at one of the two interaction regions of the DAΦNE $e^{+}e^{-}$ collider, the INFN-LNF Φ(1020)-factory; it was mainly dedicated to hypernuclear physics. The structure of the apparatus allowed to study at the same time the formation and the decay of Λ-hypernuclei by means of a high resolution magnetic spectroscopy of the emitted charged particles. In particular, for reactions occurring in the apparatus sector where ^{6}Li targets were located, for π^{+} with momentum ~ 250 MeV/c the resolution of the tracker is σ_p = (1.1±0.1) MeV/c [10] and the precision on the absolute momentum calibration is better than 0.12 MeV/c; for π^{-} with momentum ~ 130 MeV/c the resolution is $\sigma_p = (1.2 \pm 0.1)$ MeV/c and the absolute calibration is 0.2 MeV/c.

Preliminary results of the analysis of $^{6}_{\Lambda}$H production from the complete FINUDA statistics are presented here. To identify the neutron rich system production and to reduce the background, the complete production and decay reaction chain was investigated:

$$\begin{aligned} K^{-} + {}^{6}Li &\rightarrow {}^{6}_{\Lambda}H + \pi^{+} \quad (\mathrm{p}(\pi^{+}) \sim 252\ \mathrm{MeV/c}) \\ {}^{6}_{\Lambda}H &\rightarrow {}^{6}He + \pi^{-} \quad (\mathrm{p}(\pi^{-}) \sim 130 - 140\ \mathrm{MeV/c}). \end{aligned} \tag{2.1}$$

For the two reactions, occurring at rest, we can write:

$$\begin{aligned} M(K^-)+3M(p)\; + \;3M(n)-B({}^6Li) &= M({}^{6}_{\Lambda}H)+T({}^{6}_{\Lambda}H)+M(\pi^+)+T(\pi^+), \\ M({}^{6}_{\Lambda}H) &= 2M(p)+4M(n)-B({}^6He)+T({}^6He)+M(\pi^-)+T(\pi^-), \end{aligned}$$

where M are the masses, T the kinetic energies and B the binding energies.

By eliminating M(${}^{6}_{\Lambda}$H) we obtain:

$$\begin{aligned} T(\pi^+)+T(\pi^-) \;=\; & M(K^-)+M(p)-M(n)-2M(\pi) \\ & -B({}^6Li)+B({}^6He)-T({}^6He)-T({}^{6}_{\Lambda}H); \end{aligned} \tag{2.2}$$

the right hand term is independent on the ${}^{6}_{\Lambda}$H binding energy, within the FINUDA energy resolution, and $T(\pi^+)+T(\pi^-) = 203.0\pm1.3$ MeV, where 1.3 MeV is the global (statistical+systematic) kinetic energy resolution of the apparatus. Events were selected in the distribution of the sum of the energy in the region (202÷204) MeV, as indicated in the red shaded area of Figure 1.

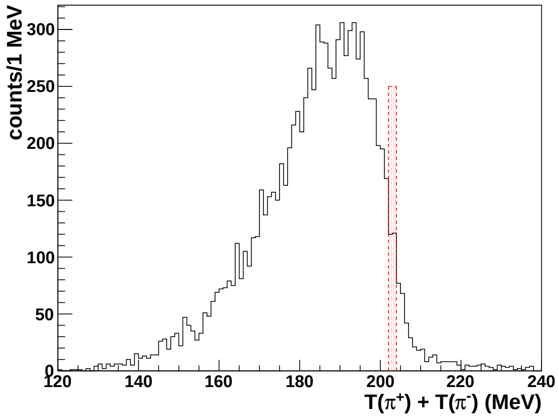

Figure 1: Distribution of raw total kinetic energy T(π^+)+T(π^-) for (π^+,π^-) coincidence events from ^{6}Li targets. The red shaded area represents the selection T(π^+)+T(π^-)=202÷204 MeV.

The p(π^+) and p(π^-) momentum distributions of the selected events are reported in figure 2; they show a smooth shape compatible with the background due to, respectively, decay and formation of the Σ^+ hyperon in the interaction of the stopped K $^-$ with a proton of the target ^{6}Li nucleus. The distributions fall to zero, respectively, at p(π^+)= 245 MeV/c and p(π^-)=145 MeV/c. These limit values correspond to ${}^{6}_{\Lambda}$H masses higher than the total mass of the ($\Lambda+{}^3\mathrm{H}+2n$) and ($\Lambda+{}^5$H) unbound systems; in figure 2 the momenta obtained from the two-body kinematics for the formation and decay of a system with the mass of the unbound (^{5}H + Λ) are indicated with blue arrows. A further cut on p(π^+)=(249÷255) MeV/c and p(π^-)=(130÷138) MeV/c was thus applied to select bound ${}^{6}_{\Lambda}$H. Three events fulfilled such selections: they are candidate to be ${}^{6}_{\Lambda}$H.

3. Results and interpretation

For each of the three selected events the ${}^{6}_{\Lambda}$H mass and binding energy, B_Λ, with respect to both

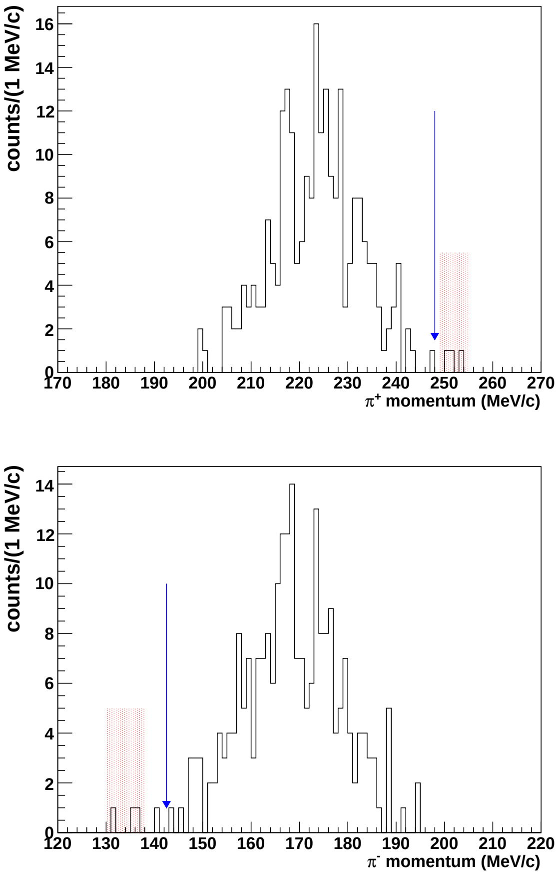

Figure 2: Distribution of π^+ (upper part) and π^- (lower part) momenta for (π^+, π^-) coincidence events with T(π^+)+T(π^-)=202÷204 MeV, from ^{6}Li targets, before acceptance correction. The blue arrows represent the momentum values for the (^{5}H + Λ) unbound system; the red shaded areas indicate the final selection regions.

the $(\Lambda + {}^3\mathrm{H} + 2n)$ and the $(\Lambda + {}^5\mathrm{H})$ systems, have been evaluated; the values are reported in Table 1.

The mean value of the $^{6}_{\Lambda}$H mass is M($^{6}_{\Lambda}$H)=5801.43±0.74. In figure 3 the mass scheme for a system of 1 proton, 4 neutrons and 1 Λ is given.

Before discussing the physical interpretation of the above results, it is mandatory to examine carefully whether the above three events could be due to physical or instrumental backgrounds that could affect the data.

The main source of instrumental background is the presence of fake tracks, misidentified as true events by the track reconstruction algorithms. To evaluate this background, events relative to target nuclei other than ^{6}Li (^{7}Li, ^{9}Be, ^{13}C, ^{16}O) were selected with the same selection criteria applied for ^{6}Li. Only one event was found, corresponding to 0.27±0.27 expected fake events from ^{6}Li targets (BGD1).

Concerning the physical backgrounds, the reaction chains that could contribute to the (π^+, π^-) coincidences with the same conditions applied to identify the production and mesonic decay

T_{tot} (MeV)	$p(\pi^{+})$ (MeV/c)	$p(\pi^{-})$ (MeV/c)	M (MeV)	B^{5}_{Λ} (MeV)	B^{3}_{Λ} (MeV)	M (MeV)	B^{5}_{Λ} (MeV)	B^{3}_{Λ} (MeV)
202.5	251.3	135.1	5802.33	3.11	1.41	5801.41	4.03	2.33
202.7	250.0	136.9	5803.45	1.99	0.29	5802.73	2.71	1.01
202.1	253.8	131.2	5799.97	5.47	3.77	5798.66	6.78	5.08

Table 1: Kinematic features, ${}^{6}_{\Lambda}$H mass, M, and binding energy with respect to ($\Lambda + {}^{5}$H), B^{5}_{Λ}, and ($\Lambda + {}^{3}H + 2n$), B^{3}_{Λ}, from production (col. 4, 5, 6) and decay (col. 7, 8, 9) reactions of the three ${}^{6}_{\Lambda}$H candidate events. $T_{tot} = T(\pi^{+}) + T(\pi^{-})$. The errors are $\sigma(T_{tot})$=1.3 MeV, $\sigma(p_{\pi^{+}})$=1.1 MeV/c, $\sigma(p_{\pi^{-}})$=1.2 MeV/c, $\sigma(M)=\sigma(B_{\Lambda})$=0.96 MeV for production reaction, =0.84 MeV for decay reaction.

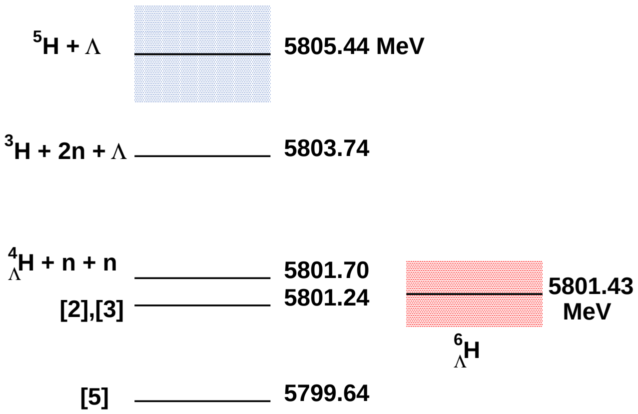

Figure 3: Left: mass scheme for a system of 1 proton, 4 neutrons and 1 Λ relative to the mass of the ^{5}H + Λ system; both partially and completely bound configurations are indicated, as calculated in Refs. [2, 3, 5]. The blue box indicates the width of ^{5}H. Right: mean value of the ${}^{6}_{\Lambda}$H ground state mass obtained in the present analysis; the red box represents the error on the mass mean value obtained from the three events.

of a bound ${}^{6}_{\Lambda}$H are:

$$\begin{aligned} K^{-} + {}^{6}Li &\rightarrow \Sigma^{+} + {}^{4}He + n + \pi^{-} \quad (\mathrm{p}(\pi^{-}) \leq 190\ \mathrm{MeV/c}), \\ \Sigma^{+} &\rightarrow n + \pi^{+} \quad (\mathrm{p}(\pi^{+}) \leq 282\ \mathrm{MeV/c}) \end{aligned} \tag{3.1}$$

and

$$\begin{aligned} K^{-} + {}^{6}Li &\rightarrow {}^{4}_{\Lambda}H + n + n + \pi^{+} \quad (\mathrm{p}(\pi^{+}) \leq 252\ \mathrm{MeV/c}), \\ {}^{4}_{\Lambda}H &\rightarrow {}^{4}He + \pi^{-} \quad (\mathrm{p}(\pi^{-}) \sim 132.8\ \mathrm{MeV/c}). \end{aligned} \tag{3.2}$$

Both reaction chains have been studied with the FINUDA simulation program fully reproducing the apparatus geometry, detection and trigger efficiency. For the chain (3.1), the interaction of K^{-} with the target nucleus has been simulated both in the quasi-free approximation ($K^{-} + p \rightarrow \Sigma^{+} + \pi^{-}$), taking into account the nucleon Fermi motion, and through the direct four-body kinematics. The chain (3.2) has been described through the four-body phase space kinematics. The simulated events were then reconstructed and submitted to the same quality cuts and same selections criteria applied in the data analysis.

Taking into account the branching fraction for the $K^-_{stop} + p \rightarrow \Sigma^+ + \pi^-$ reaction on nuclei, the $\Sigma^+ + p \rightarrow \Lambda + p$ conversion probability and the $\Sigma^+ \rightarrow n + \pi^+$ decay branching ratio, a background of 0.12±0.07 expected events on ^{6}Li targets is obtained (BGD2) from chain (3.1). The contribution of chain (3.2) was evaluated by taking into account the phase space fraction of the ${}^{4}_{\Lambda}H$ production reaction available for π^+ fulfilling the momentum selection p(π^+)=250-255 MeV/c, $4{\cdot}10^{-6}$, and the probability of the K$^-_{stop}$ to produce a ${}^{4}_{\Lambda}H$ out of a ^{6}Li target accompanied by a π^+ [11], $(11.0\pm1.4){\cdot}10^{-3}$/K$^-_{stop}$. Also the branching ratio for the mesonic decay ${}^{4}_{\Lambda}$H$\rightarrow{}^{4}$He+π^- has been considered, again determined by [11] to be 0.49. A background of 0.04±0.01 expected events on the ^{6}Li targets is obtained, negligible with respect to both the instrumental, BGD1, and chain (3.1), BGD2, contributions.

The described method allows to determine the product $R \cdot BR(\pi^-)$, where R is the ${}^{6}_{\Lambda}$H production rate per stopped K$^-$ and $BR(\pi^-)$ the branching ratio for the mesonic decay ${}^{6}_{\Lambda}H \rightarrow {}^{6}He + \pi^-$:

$$R \cdot BR(\pi^-) = \frac{N - BGD1 - BGD2}{\varepsilon(\pi^+)\ \varepsilon(\pi^-)\ K^-_{stop}(^6Li)} = (1.3 \pm 0.9) \cdot 10^{-6}/K^-_{stop}. \tag{3.3}$$

where N indicates the three candidate events, $\varepsilon(\pi^+)$ and $\varepsilon(\pi^-)$ indicate the global efficiency for the detection of π^+ and π^- evaluated by means of the full FINUDA simulation code, $K^-_{stop}(^6Li)$ is the number of K$^-$ detected at stop in ^{6}Li targets, $K^-_{stop}(^6Li) \sim 2.7 \cdot 10^7$. The value (3.3) has to be corrected for the purity of the bulk used to manufact the ^{6}Li targets used, 90%, and for the statistical reduction due to the cut on T(π^+)+T(π^-), giving $R \cdot BR(\pi^-) = (2.6 \pm 1.8) \cdot 10^{-6}/K^-_{stop}$. By assuming $BR(\pi^-)$=49%, considering the analogous decay ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^-$ [11], we find $R = (5.2 \pm 3.6) \cdot 10^{-6}/K^-_{stop}$, fully consistent with the previous upper limit obtained by FINUDA [8].

4. Conclusions

The FINUDA experiment has observed for the first time the formation and decay of the hyper superheavy hydrogen ${}^{6}_{\Lambda}$H through the (K$^-$, π^+) reaction on ^{6}Li targets. The mass of the system has been determined as M(${}^{6}_{\Lambda}$H)=5801.43±0.74, while the production rate is assessed as $R = (5.2 \pm 3.6) \cdot 10^{-6}/K^-_{stop}$.

References

[1] D.H. Davis *Nucl. Phys.* **A 754** (2005) 3c.

[2] R.H. Dalitz, R Levi Setti, *Nuovo Cimento* **30** (1963) 489.

[3] L. Majling, Nucl. Phys. **A585** (1995) 211c.

[4] Y. Akaishi *et al.*,, *Frascati Physics Series*, **XVI** (1999) 59.

[5] Y. Akaishi and K.S. Myint, *AIP Conf. Proc.* **1011** (2008) 277.

[6] K. Kubota *et al.*, *Nucl.Phys.* **A602** (1996) 327.

[7] P.K. Saha *et al.*, *Phys. Rev. Lett.* **94** (2005) 05202.

[8] M. Agnello *et al.*, *Phys. Lett.* **B640** (2006) 145.

[9] M. Agnello *et al.*, *Phys. Lett.* **B685** (2010) 247.

[10] M. Agnello *et al.*, *Phys. Lett.* **B698** (2011) 219.

[11] H. Tamura *et al.*, *Phys. Rev.* **C40** (1989) R479.