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 targets. Preliminary results are presented concerning the binding energy of this exotic nuclear system and its production rate.

1 Introduction

In 1995 Majling [1] pointed out the possible existence of bound light Λ-hypernuclei with a large neutron excess: the so called "glue-like" rôle of the Λ hyperon could produce neutron rich Λ-hypernuclei beyond the neutron stability drip line for ordinary nuclei. In particular, for systems as light as ${}^{6}_{\Lambda}$H and ${}^{7}_{\Lambda}$H, binding energies similar to those of normal

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Λ-hypernuclei in the same mass number range and production rates $\leqslant 10^{-5}/K^-_{stop}$ were predicted for the (K^-_{stop}, π^+) reaction. Akaishi and collaborators [2] 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.

From the experimental side, upper limits for the production of $^9_\Lambda$He, $^{12}_\Lambda$Be and $^{16}_\Lambda$C have been obtained [3] exploiting the (K^-_{stop}, π^+) reaction, while the production of $^{10}_\Lambda$Li has been reported [4] analysing 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 [5] on ^{6}Li, ^{7}Li and ^{12}C targets; upper limits were assessed for the production rates of $^6_\Lambda$H ($(2.5 \pm 0.4_{stat}\ ^{+0.4}_{-0.1 syst}) \cdot 10^{-5}/K^-_{stop}$), $^7_\Lambda$H and $^{12}_\Lambda$Be.

2 Experimental and analysis technique

FINUDA [6] 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 $\sim$ 250 MeV/c the resolution of the tracker is σ_p = (1.1±0.1) MeV/c [7] and the precision on the absolute momentum calibration is better than 0.12 MeV/c; for π^- with momentum $\sim$ 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:

$$(1) \qquad \begin{aligned} K^- + {}^6Li \;\; \rightarrow \;\; & {}^6_\Lambda H + \pi^+ \quad (\mathrm{p}(\pi^+) \sim 252\ \mathrm{MeV/c}) \\ & \hookrightarrow {}^6He + \pi^- \quad (\mathrm{p}(\pi^-) \sim 136.5\ \mathrm{MeV/c}). \end{aligned}$$

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):

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

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±1.3 MeV. Events were selected in the distribution of the sum of the energy in the region (202÷204) MeV. The p(π^+) and p(π^-) momentum distributions of the selected events 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. These 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 (Λ + ^{3}H + 2n) and (Λ + ^{5}H) unbound systems. 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 the (Λ + ^{3}H + 2n) and the (Λ + ^{5}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; the error is statistical only.

T_{tot} (MeV)	p(π^+) (MeV/c)	p(π^-) (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 (Λ + ^{5}H), B^5_Λ, and (Λ + ^{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(π^+)+T(π^-). The errors are $\sigma(T_{tot})$=1.3 MeV, $\sigma(p_{\pi^+})$=1.1 MeV/c, $\sigma(p_{\pi^-})$=1.2 MeV/c, σ(M)=$\sigma(B_\Lambda)$=0.96 MeV for production reaction, =0.84 MeV for decay reaction.

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. The instrumental background (BGD1) contribution was evaluated as 0.27±0.27 fake events from ^{6}Li targets.

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

$$(3) \qquad K^- + {}^6Li \rightarrow \Sigma^+ + {}^4He + n + \pi^- \quad (\mathrm{p}(\pi^-) \leqslant 190\ \mathrm{MeV/c}),$$
$$\hookrightarrow n + \pi^+ \quad (\mathrm{p}(\pi^+) \leqslant 282\ \mathrm{MeV/c})$$

$$(4) \qquad K^- + {}^6Li \rightarrow {}^4_{\Lambda}H + n + n + \pi^+ \quad (\mathrm{p}(\pi^+) \leqslant 252\ \mathrm{MeV/c}),$$
$$\hookrightarrow {}^4He + \pi^- \quad (\mathrm{p}(\pi^-) \sim 132.8\ \mathrm{MeV/c}).$$

Both reaction chains have been studied with the FINUDA simulation program fully reproducing the apparatus geometry, detection and trigger efficiency. For the chain (3) the interaction of K^- with a proton of the target nucleus has been simulated in the quasi-free approximation ($K^- + p \rightarrow \Sigma^+ + \pi^-$); the chain (4) 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$\pm$0.07 events on ^{6}Li targets is obtained (BGD2) from chain (3). The contribution of chain (4) was evaluated by taking into account the formation probability of ${}^4_{\Lambda}$H stopping a K^- in a ^{6}Li target [8], the probability of two charge-exchange reactions in sequence, (π^-, π^0) and (π^0, π^+), on the two remaining protons of the ^{6}Li nucleus and the branching ratio for the ${}^4_{\Lambda}$H$\rightarrow{}^4$He+π^- [8] ; a background of 0.0008$\pm$0.0004 events on the ^{6}Li targets is obtained, fully negligible with respect to both the instrumental, BGD1, and chain(3), 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 ${}^6_{\Lambda}H \rightarrow {}^6He + \pi^-$:

$$(5) \qquad R \cdot BR(\pi^-) = \frac{N - BGD1 - BGD2}{\epsilon(\pi^+)\ \epsilon(\pi^-)\ K^-_{stop}({}^6Li)} = (1.3 \pm 0.9) \cdot 10^{-6}/K^-_{stop}.$$

where N indicates the three candidate events, $\epsilon(\pi^+)$ and $\epsilon(\pi^-)$ 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^- stopped in ^{6}Li targets, $K^-_{stop}({}^6Li) \sim 2.7 \cdot 10^7$. The value (5) 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 ${}^4_{\Lambda}H \rightarrow {}^4He + \pi^-$ [8], we find $R = (5.2 \pm 3.6) \cdot 10^{-6}/K^-_{stop}$, fully consistent with the previous upper limit obtained by FINUDA [5].

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 $R = (5.2 \pm 3.6) \cdot 10^{-6}/K^{-}_{stop}$.

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