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Search for the neutron-rich hypernucleus $^{9}_{\Lambda}$He

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Search for the neutron-rich hypernucleus $^{9}_{\Lambda}$He is reported by the FINUDA experiment at DAΦNE, INFN-LNF, studying (π^+,π^-) pairs in coincidence from the $K^-_{\mathrm{stop}} + {}^9\mathrm{Be} \to {}^9_\Lambda\mathrm{He} + \pi^+$ production reaction followed by $^9_\Lambda\mathrm{He} \to {}^9\mathrm{Li} + \pi^-$ weak decay. An upper limit of the production rate of $^9_\Lambda$He undergoing this two-body π^- decay is determined to be $(2.3 \pm 1.9) \times 10^{-6}/K^-_{\mathrm{stop}}$ at the 90% confidence level.

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In recent papers we reported [1] and described in detail [2] the first experimental evidence for the existence of hyper superheavy hydrogen $^6_\Lambda$H. Three candidate events for such a particle-stable nuclear system were uniquely identified in the FINUDA experiment at DAΦNE, Frascati (Italy), by observing π^+ mesons from the (K^-,π^+) reaction on ^{6}Li targets, in coincidence with π^- mesons from $^6_\Lambda\mathrm{H} \to {}^6\mathrm{He} + \pi^-$ weak decay. The $^6_\Lambda$H binding energy with respect to $^5\mathrm{H} + \Lambda$ was determined jointly from production and decay processes to be $B_\Lambda(^6_\Lambda\mathrm{H}) = (4.0 \pm 1.1)$ MeV, assuming that the ^{5}H ground-state (g.s.) resonance lies at 1.7 MeV above the $^3\mathrm{H} + 2n$ lowest neutron emission threshold [3]. We remark that $^6_\Lambda$H is a particle-stable nuclear system with the highest $N/Z = 4$ value ($(N+\Lambda)/Z = 5$) measured so far, higher than for the archetype neutron-rich nucleus ^{11}Li. Since ^{7}Li and ^{9}Be targets were used in the same data taking in which $^6_\Lambda$H was produced on ^{6}Li targets, with a similar number of stopped K^-, we examined whether the method applied to the successful search for $^6_\Lambda$H could be extended to $^7_\Lambda$H and $^9_\Lambda$He. The case of $^7_\Lambda$H was dismissed, because the daughter nucleus ^{7}He produced in the two-body weak decay $^7_\Lambda\mathrm{H} \to {}^7\mathrm{He} + \pi^-$ is particle-unstable, making nonapplicable the experimental method that is briefly outlined in the following. However, the method could be applied in the case of $^9_\Lambda$He, because both ^{9}Li g.s. and first excited state at 2.691 MeV are particle stable [4], allowing thus a two-body weak decay $^9_\Lambda\mathrm{He} \to {}^9\mathrm{Li} + \pi^-$.

The neutron-rich $^9_\Lambda$He hypernucleus is one of the exotic Λ-hypernuclear species considered decades ago by Dalitz and Levi Setti [5] and by Majling [6], who estimated the binding-energy $B_\Lambda(^9_\Lambda\mathrm{He}) = 8.5$ MeV. This value, coinciding with $B_\Lambda(^9_\Lambda\mathrm{Li})$ [7], is based on the assumption that the increased neutron excess in $^9_\Lambda$He with respect to $^9_\Lambda$Li does not induce irregularities in the known binding energy systematics. The assumption is consistent with the similarity of B_Λ values for $^6_\Lambda$H [1,2] and $^6_\Lambda$He [7] and for $^7_\Lambda$He [8] and $^7_\Lambda$Li [7]. Millener's recent shell-model study of p-shell B_Λ values, Table 2 in Ref. [9], suggests that $B_\Lambda(^9_\Lambda\mathrm{He}) \approx B_\Lambda(^9_\Lambda\mathrm{Li})$ to within less than 0.1 MeV. We therefore adopt the value $B_\Lambda(^9_\Lambda\mathrm{He}) = 8.5$ MeV as a working hypothesis. Figure 1 shows the expected particle-stable $^9_\Lambda$He levels, together with the

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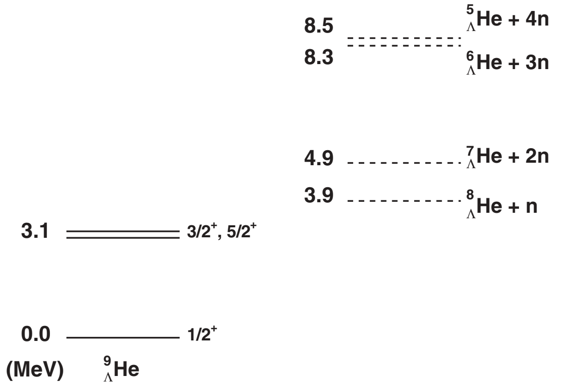

FIG. 1. Anticipated $^9_\Lambda$He energy level scheme below the lowest neutron emission threshold, together with higher neutron emission thresholds. Note the schematically marked $^9_\Lambda$He excited doublet that is based on ^{8}He (particle-unstable) first excitation 2^+ at ≈3.1 MeV [4].

neutron emission thresholds below the 8.5-MeV Λ emission threshold.

We outline now briefly the experimental method adopted in the search for $^9_\Lambda$He. The DAΦNE ϕ-Factory in Frascati uses e^+e^- collisions at total c.m. energy $\sqrt{s} = 1020$ MeV to produce ϕ mesons that decay into (K^+, K^-) pairs with a 49% branching ratio. The resulting K^- mesons of kinetic energy 16.1 ± 0.5 MeV can be stopped in nuclear targets. In the FINUDA experiment, a total of 2.5×10^7 K^- mesons were detected as stopped in two ^{9}Be targets, 2 mm thick. The FINUDA detector has been described in detail recently in Refs. [2,10]. $^9_\Lambda$He can be produced in the following two-body reaction:

$$K^-_{\text{stop}} + {}^9\text{Be} \rightarrow {}^9_\Lambda\text{He} + \pi^+. \qquad (1)$$

Assuming $B_\Lambda({}^9_\Lambda\text{He}) = 8.5$ MeV, it is straightforward to evaluate the momentum $p_{\pi^+} = 257.5$ MeV/c and kinetic energy $T_{\pi^+} = 153.3$ MeV for a π^+ meson emitted in Eq. (1). The two-body weak decay

$${}^9_\Lambda\text{He}_{\text{g.s.}} \rightarrow {}^9\text{Li}_{\text{g.s.}} + \pi^- \qquad (2)$$

should then produce a π^- meson with $p_{\pi^-} = 116.9$ MeV/c and $T_{\pi^-} = 42.5$ MeV. We note that $^9_\Lambda$He could be produced in the reaction (1) also in one of the excited doublet levels marked schematically in Fig. 1 that, if particle-stable, would γ decay to $^9_\Lambda\text{He}_{\text{g.s.}}$ which would then decay weakly according to Eq. (2). However, one or both of these $^9_\Lambda$He doublet levels could prove to be isomeric, similar to what is believed to occur for $^7_\Lambda$He [7]. One has to allow for such a scenario when considering the spread of the $\pi^\pm$ accepted momenta and kinetic energies.

The formation (1) and decay (2) reactions both occur at rest, since the stopping time of $^9_\Lambda$He in the material (Be) is shorter than its lifetime which is of the order of 2.6×10^{-10} s (the free Λ lifetime). Momentum conservation is then automatically ensured and energy conservation is expressed explicitly for Eq. (1),

$$\begin{aligned} &M(K^-) + 4M(p) + 5M(n) - B({}^9\text{Be}) \\ &\quad = M\big({}^9_\Lambda\text{He}\big) + T\big({}^9_\Lambda\text{He}\big) + M(\pi^+) + T(\pi^+), \end{aligned} \qquad (3)$$

and for Eq. (2),

$$\begin{aligned} M\big({}^9_\Lambda\text{He}\big) &= 3M(p) + 6M(n) - B({}^9\text{Li}) + T({}^9\text{Li}) \\ &\quad + M(\pi^-) + T(\pi^-), \end{aligned} \qquad (4)$$

in which M stands for mass, T for kinetic energy, and B for nuclear binding energy. Combining Eqs. (3) and (4) in order to eliminate $M({}^9_\Lambda\text{He})$, we get the following equation:

$$\begin{aligned} T(\pi^+) + T(\pi^-) &= M(K^-) + M(p) - M(n) - 2M(\pi) \\ &\quad - B({}^9\text{Be}) + B({}^9\text{Li}) - T({}^9\text{Li}) - T\big({}^9_\Lambda\text{He}\big). \end{aligned} \qquad (5)$$

All the terms on the right-hand side are known constants, except for $T({}^9_\Lambda\text{He})$ and $T({}^9\text{Li})$ that can be evaluated from momentum and energy conservation and depend on the unknown value of $B_\Lambda({}^9_\Lambda\text{He})$.

A variation of $B_\Lambda({}^9_\Lambda\text{He})$ between 0 and 10 MeV introduces a change of ~0.1 MeV in $T(\pi^+) + T(\pi^-)$ (5), corresponding to a sensitivity of 10 keV per MeV of $B_\Lambda({}^9_\Lambda\text{He})$. This change is much smaller than the measured energy resolutions for π^+ (deduced from the 235.6 MeV/c monochromatic μ^+ line in $K_{\mu 2}$ decay) and π^- (deduced from the 132.8 MeV/c monochromatic π^- line in the two-body $^4_\Lambda$H mesonic decay): $\sigma_{T(\pi^+)} = 0.96$ MeV and $\sigma_{T(\pi^-)} = 0.84$ MeV. The FINUDA energy resolution for a (π^+, π^-) pair in coincidence is $\sigma_T = 1.3$ MeV [2]. We assume a value of $B_\Lambda({}^9_\Lambda\text{He}) = 8.5$ MeV [6]; therefore $T_{\text{sum}} \equiv T(\pi^+) + T(\pi^-) = 195.8 \pm 1.3$ MeV.

Then we consider, for the coincidence (π^+, π^-) events, only those for which the sum of the kinetic energies T_{sum} assumes values in the range 194.5–197.5 MeV. The half-width of this interval corresponds to 1.15 σ_T, in order to be selective on possible background events and benefiting from the excellent stability of the FINUDA magnetic spectrometry. A two-dimensional plot of these selected events is shown in Fig. 2. Events associated with the formation of $^9_\Lambda$He should fall in the hatched (red) rectangle in the figure, with $p_{\pi^+} = (253.5\text{–}259)$ MeV/c and $p_{\pi^-} = (114.5\text{–}122)$ MeV/c.

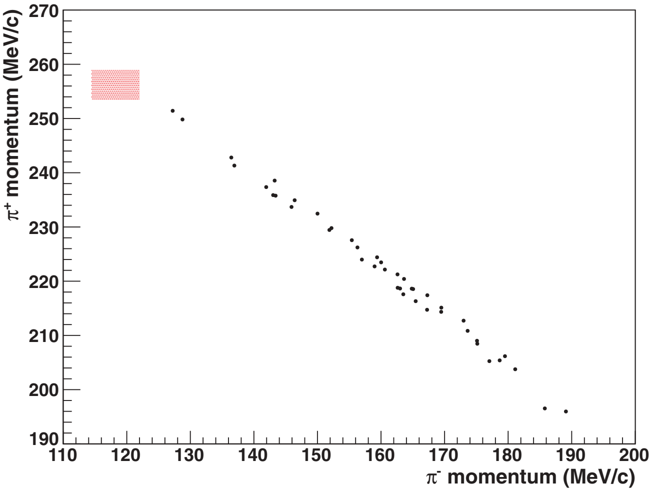

FIG. 2. (Color online) π^+ momentum vs π^- momentum for ^{9}Be target events with $T_{\text{sum}} = (194.5\text{–}197.5)$ MeV. The shaded (red) rectangle indicates the position of events with $p_{\pi^+} = (253.5\text{–}259)$ MeV/c and $p_{\pi^-} = (114.5\text{–}122)$ MeV/c.

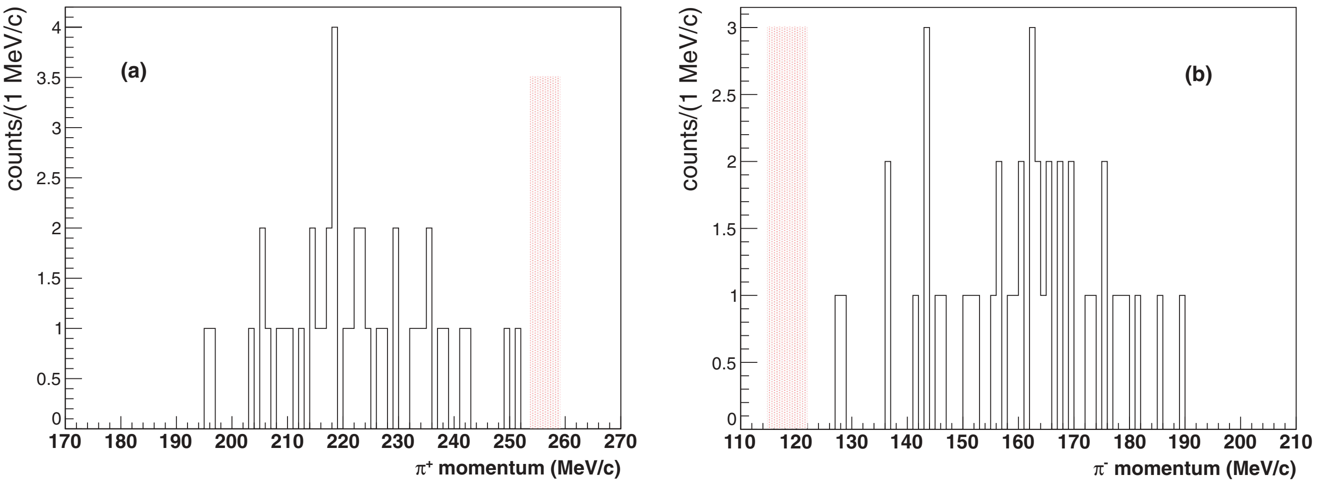

FIG. 3. (Color online) π^+ momentum (a) and π^- momentum (b) distributions for ^{9}Be target events with $T_{\rm sum} = (194.5\text{–}197.5)$ MeV. The shaded (red) rectangles highlight pion momenta $p_{\pi^+} = (253.5\text{–}259)$ MeV/c and $p_{\pi^-} = (114.5\text{–}122)$ MeV/c, corresponding to $B_\Lambda({}^{9}_{\Lambda}\text{He}) =$ 5–10 MeV.

These values correspond to pion momenta that span values of $B_\Lambda({}^{9}_{\Lambda}\text{He})$ between 5 and 10 MeV.

Figure 3 shows the projections on the two axes of the distribution of Fig. 2: there are clearly no events satisfying the conditions required by the formation and decay of ${}^{9}_{\Lambda}$He with $B_\Lambda({}^{9}_{\Lambda}\text{He}) \geqslant 5$ MeV; recall from Fig. 1 that $B_\Lambda({}^{9}_{\Lambda}\text{He}) =$ 5 MeV is about 1 MeV above the lowest neutron emission threshold expected for ${}^{9}_{\Lambda}$He.

Because no events that could be attributed to the existence of a bound ${}^{9}_{\Lambda}$He were found, we did not follow the analysis done for ${}^{6}_{\Lambda}$H [2] in which extensive calculations were performed on possible backgrounds that would mimic the expected true events. Events filling the full distribution of Fig. 2 are certainly attributable primarily to reactions with the production of a quasi-free Σ^+, but it was outside the scope of the present analysis to reproduce the shape and strength of this distribution.

Given the experimental procedure described above, it was possible to derive an upper limit for $R \cdot \text{BR}(\pi^-)$, where R is ${}^{9}_{\Lambda}$He production rate per stopped K^- in reaction (1) and $\text{BR}(\pi^-)$ is the branching ratio (BR) for ${}^{9}_{\Lambda}$He two-body weak decay (2):

$$R \cdot \text{BR}(\pi^-) \leqslant \frac{N}{\epsilon(\pi^+)\,\epsilon(\pi^-)\,K^-_{\rm stop}(^9\text{Be})} = (1.6 \pm 1.3) \times 10^{-6}/K^-_{\rm stop}. \qquad (6)$$

Here, N is the expected mean value of the observation for which a null observation is 10% probable [upper limit at 90% confidence level (C.L.)], and $\epsilon(\pi^+)$ and $\epsilon(\pi^-)$ indicate the global efficiencies for π^+ and π^-, respectively, including detection efficiency, geometrical and trigger acceptances and pattern recognition, reconstruction, and selection efficiencies, all of which have been evaluated by means of the full FINUDA simulation code, well tested in calculations for other reactions in similar momentum ranges [11–13]. $K^-_{\rm stop}(^9\text{Be})$ is the number of K^- detected at stop in ^{9}Be targets.

For the evaluation of the upper limit a correction for the 1.15 σ_T cut applied to $T(\pi^+) + T(\pi^-)$ has to be taken into account and a correction for the fraction of ${}^{9}_{\Lambda}$He decaying in flight has to be applied too, which is estimated to be smaller than 8% [14]. The $R \cdot \text{BR}(\pi^-)$ value, corrected for both effects is $R \cdot \text{BR}(\pi^-) < (2.3 \pm 1.9) \times 10^{-6}/K^-_{\rm stop}$.

To derive the upper limit R for the production rate of ${}^{9}_{\Lambda}$He particle-stable levels, we need to know the branching ratio $\text{BR}(\pi^-)$ for the two-body weak decay ${}^{9}_{\Lambda}\text{He}_{\rm g.s.} \rightarrow {}^9\text{Li}_{\rm g.s.} + \pi^-$. The other possible two-body decay, to ^{9}Li(2.691 MeV) with $p_{\pi^-} = 112.6$ MeV/c corresponding to the value $B_\Lambda =$ 8.5 MeV assumed here, is outside of the p_{π^-} cut imposed in the present search and, therefore, it does not contribute to $\text{BR}(\pi^-)$. Nevertheless, inspection of the π^- momentum distribution in Fig. 3(b) suggests that this two-body decay too is not observed in our measurement. In the absence of published evaluations of the branching ratio for the weak decay ${}^{9}_{\Lambda}\text{He}_{\rm g.s.} \rightarrow {}^9\text{Li}_{\rm g.s.} + \pi^-$ in which a $1s$ Λ is transformed to a $1p$ proton, we follow Ref. [15] and evaluate

$$\Gamma\left({}^{9}_{\Lambda}\text{He}_{\rm g.s.} \rightarrow {}^9\text{Li}_{\rm g.s.} + \pi^-\right) = 0.261\Gamma_\Lambda, \qquad (7)$$

where Γ_Λ is the free-Λ decay rate which approximates fairly the total Λ-hypernuclear decay rate in the relevant mass range [16]. For completeness, we give also the rate evaluated for decay to ^{9}Li (2.691 MeV):

$$\Gamma\left({}^{9}_{\Lambda}\text{He}_{\rm g.s.} \rightarrow {}^9\text{Li}_{\rm exc.} + \pi^-\right) = 0.094\Gamma_\Lambda. \qquad (8)$$

Using the branching ratio value $\text{BR}(\pi^-) = 0.261$ from Eq. (7), we obtain the following upper limit for the production of ${}^{9}_{\Lambda}$He,

$$R < (2.3 + 1.9)/0.261 \times 10^{-6}/K^-_{\rm stop} = 1.6 \times 10^{-5}/K^-_{\rm stop}, \qquad (9)$$

at 90% C.L. This improves by over an order of magnitude the previous upper limit set in an experiment performed at the High Energy Accelerator Research Organization, Tsukuba, Japan (KEK) [17].

Table I summarizes the lowest upper limits on production rates for neutron-rich hypernuclei in the p shell from searches done at KEK [17] and during the first data taking of FINUDA

TABLE I. Upper limits on rates R per stopped K^-, for production of p-shell neutron-rich hypernuclei in the $(K^-_{\rm stop}, \pi^+)$ reaction.

${}^{7}_{\Lambda}$H [18]	${}^{9}_{\Lambda}$He (Present work)	${}^{12}_{\Lambda}$Be [18]	${}^{16}_{\Lambda}$C [17]
5.4×10^{-5}	1.6×10^{-5}	2.4×10^{-5}	6.2×10^{-5}

[18]; to compare directly to Eq. (9), the statistical error in Ref. [18] has been added. These upper limits were deduced through the analysis of inclusive spectra of π^+ mesons emitted following the capture of K^- mesons at rest by nuclei and looking for peaks in relevant momentum regions. We note that all of these upper limits do not go below the value $R = 10^{-5}/K^-_{\rm stop}$, higher than the ${}^{6}_{\Lambda}$H production rate deduced from the observation of three ${}^{6}_{\Lambda}$H candidate events [1]. Clearly, the observation of neutron-rich hypernuclei by studying inclusive spectra of π^+ mesons was hindered in these experiments by the overwhelming background from reactions leading to the production of a Σ^+ hyperon on one or two correlated protons. The technique of taking in coincidence also a π^- meson from the weak decay of the produced neutron-rich hypernucleus, while applying a narrow selection on the sum of the kinetic energies of the (π^+, π^-) pair, allowed us to distinguish for the first time ${}^{6}_{\Lambda}$H and to improve by over one order of magnitude the upper limit on the production of ${}^{9}_{\Lambda}$He reported from KEK [17]. We note that the method of enforcing a π^- weak decay coincidence suffers from the theoretical uncertainty associated with deducing the particular two-body weak decay branching ratio BR. However, it has been shown [13] that the available relevant theoretical calculations [15,19,20] are fully reliable.

There are no detailed theoretical calculations on the production rates for light neutron-rich hypernuclei in K^- capture at rest. From experiment, the production rate of ${}^{6}_{\Lambda}$H [1,2] is 2 to 3 orders of magnitude lower than those for the production of bound states of "ordinary" light hypernuclei in $(K^-_{\rm stop}, \pi^-)$ reactions [11]. These new measurements by FINUDA provide a new impetus that should stimulate further efforts in this field both experimentally and theoretically.

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