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SEARCH FOR NEUTRON-RICH HYPERNUCLEI IN FINUDA: PRELIMINARY RESULTS

The FINUDA Collaboration *

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ABSTRACT

The FINUDA experiment allows to investigate the existence of some rare hypernuclear states predicted by the theory and never observed up to now, the neutron-rich hypernuclei. These objects are produced in very rare events (predicted production rates $\sim 10^{-6} \div 10^{-5}/\mathrm{K}^-_{stop}$) and their formation is associated with a π^+ in the final state, whose momentum spectrum will provide information on their energy. The preliminary analysis of the π^+ spectra obtained for the employed targets (^{12}C, ^{6}Li, ^{7}Li) from the first data taking is presented; the results and the prospects for the future analysis will be discussed.

1 Introduction

The FINUDA experiment, performed at the e$^+$ e$^-$ collider DAΦNE of the Laboratori Nazionali di Frascati, is mainly aimed at studying the spectroscopy and decays of Λ hypernuclei, produced by means of K$^-$ from the reaction e$^+$ + e$^-$ $\longrightarrow \phi(1020) \longrightarrow$ K$^+$ + K$^-$ on different targets. A description of the FINUDA detector may be found in [1), 2)] and references therein.

In the wide FINUDA physics program, the search for "neutron-rich" hypernuclei is foreseen. The existence of Λ-hypernuclei with a large neutron excess ($N/Z \gtrsim 2\ N/Z$[ordinary nuclei]) has been theoretically predicted [3)] but not observed up to now. Their formation should be possible since the Λ hyperon does not undergo the Pauli principle costraints, providing an "extra-binding" energy to the nuclear structure and allowing a larger number of neutrons to be bound with respect to the ordinary nuclei.

The search of neutron-rich hypernuclei is a very relevant scientific task, in order to fill up the chart of nuclei in the strangeness = -1 sector and for its feedback with other fields of physics, for example in the study of phenomena related to the very high nuclear density of neutron stars [4)] in astrophysics.

2 Neutron-rich hypernuclei production in FINUDA

FINUDA is an ideal laboratory to investigate the existence of hypernuclei with high N/Z ratios, that can be produced via the (K^-_{stop},π^+) reactions in the targets, according to two elementary reaction mechanisms:

1) *double charge exchange*:

$$\mathrm{K}^- + \mathrm{p} \longrightarrow \Lambda + \pi^0\ ; \qquad \pi^0 + \mathrm{p} \longrightarrow \mathrm{n} + \pi^+$$

2) *strangeness exchange* $+\ \Sigma - \Lambda$ *coupling*:

$$\mathrm{K}^- + \mathrm{p} \longrightarrow \Sigma^- + \pi^+\ ; \qquad \Sigma^- + \mathrm{p} \longleftrightarrow \Lambda + \mathrm{n}\ .$$

Both mechanisms produce in the final state a π^+ and a Λ hypernucleus with A and $Z-2$ (starting from a target nucleus with A and Z); the global production reactions on ^{12}C, ^{6}Li and ^{7}Li respectively are:

$$\begin{array}{llll} \mathrm{K}^- + {}^{12}\mathrm{C} & \longrightarrow & {}^{12}_{\Lambda}\mathrm{Be} + \pi^+ & (N/Z = 1.75) \\ \mathrm{K}^- + {}^{6}\mathrm{Li} & \longrightarrow & {}^{6}_{\Lambda}\mathrm{H} + \pi^+ & (N/Z = 4) \\ \mathrm{K}^- + {}^{7}\mathrm{Li} & \longrightarrow & {}^{7}_{\Lambda}\mathrm{H} + \pi^+ & (N/Z = 5). \end{array} \tag{1}$$

The final π^+ momentum is directly related to the Λ binding energy B_Λ of ${}^{12}_{\Lambda}$Be, ${}^{6}_{\Lambda}$H, ${}^{7}_{\Lambda}$H by means of momentum and energy conservation, as for the π^- in the case of $(\mathrm{K}^-_{stop},\pi^-)$ reactions mainly studied in FINUDA [1].

At present, our knowledge about neutron-rich hypernuclei properties, such as binding energies and production rates for the reactions (1), is rather poor: the only available experimental datum is an upper limit for the ${}^{12}_{\Lambda}$Be production rate, measured at KEK in 1995 [5]. The whole set of known experimental and theoretical data is listed in Tab. 1.

Table 1: *Available experimental and theoretical data for the neutron-rich hypernuclei to be searched for in FINUDA: ${}^{12}_{\Lambda}Be$, ${}^{6}_{\Lambda}H$ and ${}^{7}_{\Lambda}H$ (EX = experimental value, TH = evaluated from theory, XT = extrapolated theoretical value).*

Hyper-nucleus	**Nuclear State**	**Λ Binding Energy B_Λ**	**π^+ momentum**	**Production rate per K^-_{stop}**
${}^{12}_{\Lambda}$Be	1^-	11.4 MeV (XT) [3]	261.8 MeV/c	$< 6.1\cdot10^{-5}$ (EX) [5] $1.8\cdot10^{-5}$ (TH) [6]
	0^+	-	-	$0.6\cdot10^{-5}$ (TH) [6]
${}^{6}_{\Lambda}$H	0^+	5.8 MeV (TH) [7] 4.2 MeV (XT) [3]	254.1 MeV/c 252.3 MeV/c	- -
${}^{7}_{\Lambda}$H	0^+	5.2 MeV (XT) [3]	245.3 MeV/c	-

3 Data analysis and preliminary results

¿From October 2003 to March 2004 FINUDA has successfully carried out its first round of data taking at DAΦNE, collecting about ~ 220 pb^{-1} of integrated luminosity. The whole collected data have been analyzed, with a not yet refined analysis code, to extract first information about neutron-rich hypernuclei production.

The candidate events have been selected requesting a stopped K^- in the selected target and a successfully reconstructed positive charge track associated to K$^-$ itself. The positive charge track is identified as a π^+ by means of the energy loss $\Delta E/\Delta x$ in the outer silicon microstrip detector and the particle time of flight (TOF) as measured by the inner and outer scintillator barrels (see the detector description in [1), 2)]). An example of reconstructed candidate event is shown in Fig. 1.

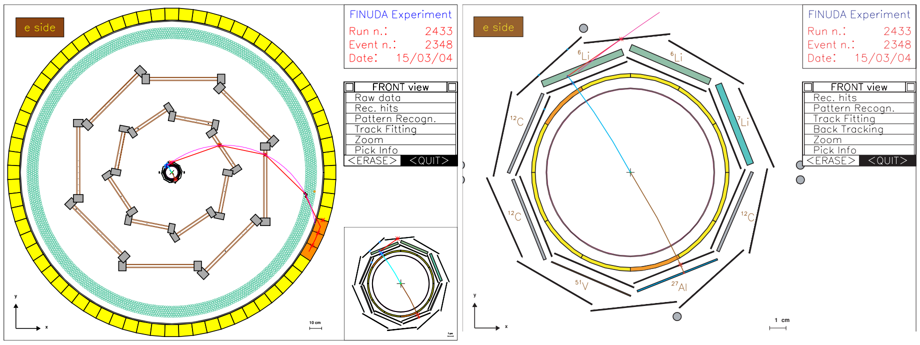

Figure 1: *Reconstructed candidate event for the neutron-rich hypernucleus formation: full detector view and enlarged view of the vertex zone. The fitted track of the π^+ coming out from the ^{6}Li target (where K$^-$ has stopped) is also shown.*

Keeping in mind the production mechanisms (1), inclusive momentum spectra have been studied for the π^+ coming out from ^{12}C, ^{6}Li and ^{7}Li targets; the spectra have been observed in the region around $p \sim 250$ MeV/c (region of interest ROI), corresponding to the theoretical values of B$_\Lambda$ in the ground state for the $^{12}_{\Lambda}$Be, $^{6}_{\Lambda}$H and $^{7}_{\Lambda}$H hypernuclei (see Tab. 1). The ROI width Δp has been set to $\pm\, 2\, \sigma_p$ around the central value, where σ_p is the spectrometer momentum resolution. The resulting spectra are shown in Fig. 2, ordered by target nucleus; the shaded zones mark the selected ROI.

As it can be seen from the figure, at this preliminary stage there is no evidence of peaks to be ascribed to the formation of neutron-rich hypernuclei in the ROI yet; this is somewhat expected, since inclusive spectra would still include a large background due to other reactions producing a π^+.

Nevertheless, it is possible to extract from the data an upper limit for the neutron-rich hypernuclei $^{12}_{\Lambda}$Be, $^{6}_{\Lambda}$H, $^{7}_{\Lambda}$H production rates, in the following way. First, an evaluation of the π^+ count rate R_π in the ROI is possible, exploiting the FINUDA unique feature of working with opposite (K$^+$, K$^-$) pairs. In fact, about the same number of K$^+$ and K$^-$ is expected to stop in a given target, and the μ^+ produced in the K$^+ \to \mu^+ + \nu_\mu$ decay with branching ratio $BR =$

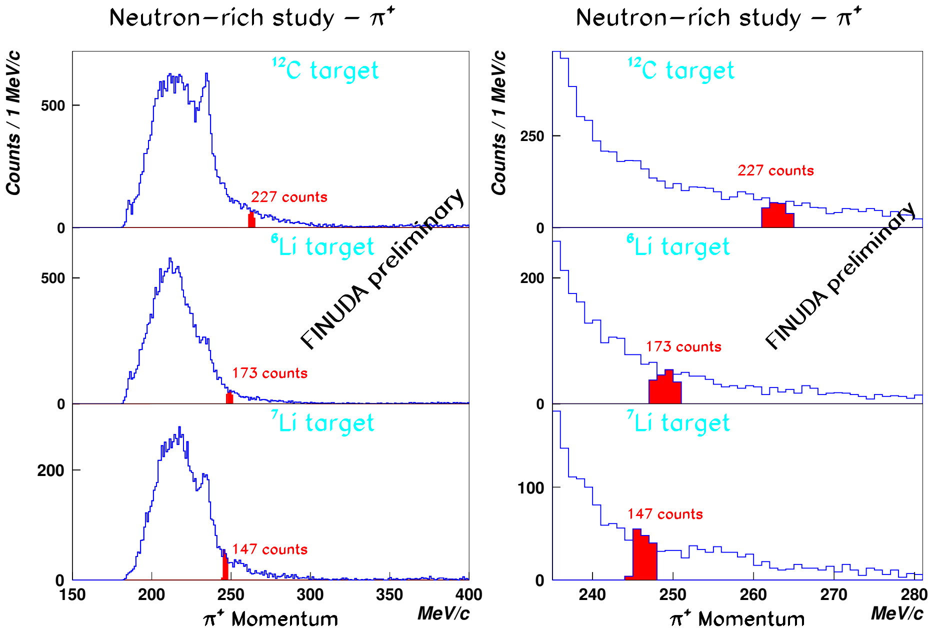

Figure 2: π^+ *momentum spectra obtained from* ^{12}C, ^{6}Li *and* ^{7}Li *targets (full view and enlarged view in the regions of interest ROI).*

0.63 may be used for normalization purposes. In this respect, the rate R_π can be written as [9]:

$$R_\pi \simeq \frac{N_\pi \cdot BR \cdot \varepsilon_\mu \cdot \alpha_{\mathrm{T}}}{N_\mu \cdot \varepsilon_\pi}\,, \tag{2}$$

where N_π is the number of reconstructed π^+ falling into the ROI shown in Fig. 2, N_μ is the μ^+ count number for the same target, ε_μ and ε_π are the total reconstruction efficiencies for μ^+ and π^+ respectively ($\varepsilon_\mu \approx \varepsilon_\pi$), and $\alpha_{\mathrm{T}} \approx 0.50 \pm 0.05$ is the μ^+ acceptance due to the trigger time gate.

On the other side, from statistical considerations, it can be shown that the absence of a neutron-rich "signal" in the spectra implies (at a confidence level of $k\sigma$) a signal-to-background ratio S/B satisfying the condition [9]:

$$(S+B) - k\sqrt{S+B} \leq B + k\sqrt{B} \quad \Longrightarrow \quad \frac{S}{B} \leq k \cdot \frac{2\sqrt{B}+k}{B}\,, \tag{3}$$

Assuming that the observed N_π counts are entirely due to background, we may set $B \simeq N_\pi$ and obtain from (2) and (3) the following relation, fixing the upper limit U.L. for the hypernucleus production rate $(S/B) \cdot R_\pi$:

$$\frac{S}{B} \cdot R_\pi \lesssim k \cdot \frac{2\sqrt{N_\pi} + k}{N_\pi} \cdot R_\pi \simeq k \cdot \frac{2\sqrt{N_\pi} + k}{N_\mu} \cdot BR \cdot \alpha_{\mathrm{T}} = \mathrm{U.L.} \qquad (4)$$

The U.L. values obtained from the (4) are shown in Tab. 2. The evaluation has been done for different confidence levels (90% or $k = 1.645$, 2σ, 3σ), different ROI widths (Δp corresponding to actual momentum resolution 0.9% FWHM and expected final momentum resolution 0.35% FWHM) and different π^+ PID methods. The estimated uncertainties are of the order of $\approx$ 10%.

Table 2: *Upper limits for the hypernucleus formation rate evaluated by eq. (4).*

U. L. value ($\cdot 10^{-5}$)	**90% C.L.**		**2 σ C.L.**		**3 σ C.L.**		
	$\Delta E/\Delta x$ **ONLY**	$\Delta E/\Delta x$ **+TOF**	$\Delta E/\Delta x$ **ONLY**	$\Delta E/\Delta x$ **+TOF**	$\Delta E/\Delta x$ **ONLY**	$\Delta E/\Delta x$ **+TOF**	
$^{12}_{\Lambda}\mathbf{Be}$	2.6	2.1	3.2	2.6	4.9	4.0	**Actual**
$^{6}_{\Lambda}\mathbf{H}$	3.5	2.9	4.3	3.6	6.6	5.6	***p* resol.**
$^{7}_{\Lambda}\mathbf{H}$	4.9	4.3	6.1	5.3	9.4	8.3	**(0.9%)**
$^{12}_{\Lambda}\mathbf{Be}$	1.6	1.3	2.0	1.6	3.1	2.5	**Nominal**
$^{6}_{\Lambda}\mathbf{H}$	2.1	1.8	2.6	2.2	4.1	3.5	***p* resol.**
$^{7}_{\Lambda}\mathbf{H}$	3.3	2.8	4.1	3.5	6.5	5.6	**(0.35%)**

The results are very encouraging, despite the fact that we are at a preliminary analysis stage, in which we are looking at the inclusive spectra only, before applying any coincidence technique. In fact, it is already possible to give, for the $^{12}_{\Lambda}$Be production rate, a preliminary U.L. value of $2.1 \cdot 10^{-5}$ at a 90% C.L. with the actual momentum resolution, that improves the KEK result ($6.1 \cdot 10^{-5}$ [5])) of about a factor ~ 3; furthermore, it has to be stressed that the upper limits shown in Tab. 2 for the $^{6}_{\Lambda}$H and $^{7}_{\Lambda}$H production rates are measured for the first time for these hypernuclei.

4 Conclusions and prospects

The preliminary results reported in this paper are promising and demonstrate the potentiality of FINUDA in carrying out the search of neutron-rich hypernuclei. Some important improvements in the data analysis are foreseen, both from the events reconstruction and the coincidence-anticoincidence techniques in study, in order to reduce the background in the ROI of the π^+ momentum spectra.

Further refinements in the upper limit values are expected after the next data analysis and the possibility to evidence structures to be ascribed to neutron-rich hypernuclei in the π^+ spectra is expected.

References

1. M. Agnello *et al*, **LNF-03/23 (P)** (2003), to be published on Nucl. Phys. B (Proc. Supp.).

2. The FINUDA Collaboration, *First results of FINUDA on Hypernuclear Spectroscopy*, these proceedings.

3. L. Majling, Nucl. Phys. A **585**, 211c (1995).

4. Y. Yamamoto *et al*, Nucl. Phys. A **691**, 432c (2001).

5. K. Kubota *et al*, Nucl. Phys. A **602**, 327 (1996).

6. T. Tretyakova *et al*, Nucl. Phys. A **691**, 51c (2001).

7. Y. Akaishi *et al*, Frascati Phys. Ser. Vol. **XVI**, 59 (1999).

8. The FINUDA Collaboration, *Examining* Σ*-bound states with FINUDA*, these proceedings.

9. FINUDA note, in preparation.