First results from the FINUDA experiment

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[†]This paper is dedicated to the memory of V. Filippini

This paper provides a review of the first results obtained by the FINUDA Collaboration in the field of the hypernuclear physics. They range from the spectroscopic study of several Λ-hypernuclei to the observation of their, both mesonic and non-mesonic, decay modes. Hints on rare hypernuclear two-body decays, on neutron-rich hypernuclei and on deeply-bound kaonic nuclei are also reported.

1. Introduction

FINUDA [1] (italian acronym for "FIsica NUcleare a DAΦNE") is a revolutionary apparatus conceived to carry on a nuclear physics experiment at a collider. This unusual approach was triggered [2] by the construction of DAΦNE [3], the ϕ-factory operating at the INFN National Laboratory of Frascati (LNF): the leading idea is to produce Λ-hypernuclei by exploiting the low energy ($\sim 16\ MeV$) K^- from the decay of ϕ mesons, produced at a rate of $\sim 300\ s^{-1}$ at the present luminosity of the DAΦNE collider ($\sim\ 7 \times 10^{31}\ cm^{-2} s^{-1}$) [4].

By stopping these really slow ($\sim 127\ MeV/c$) K^- in very thin ($\sim 200 \div 300\ mg/cm^2$) nuclear targets it is possible to produce a large variety of Λ-hypernuclei. The main aim of the experiment is to simultaneously measure the excitation energy spectra of the produced Λ-hypernuclei, the lifetime of the Λ hyperon embedded in nuclear matter and the partial widths (Γ_π, Γ_{np} and Γ_{nn}) for both mesonic and non-mesonic decay channels.

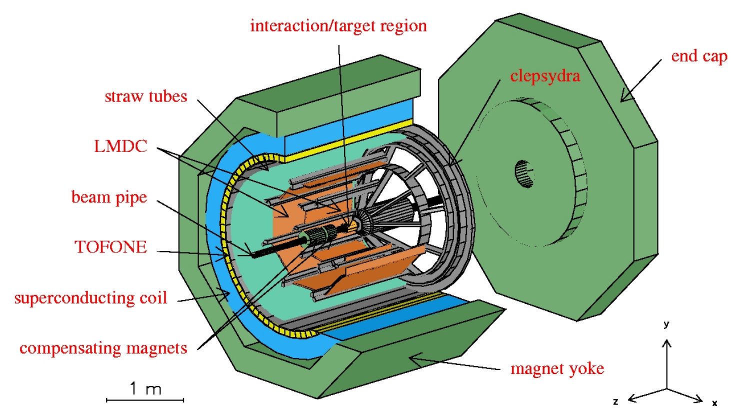

Figure 1: Sketch of the FINUDA apparatus.

Thanks to a careful design, the FINUDA apparatus (see Fig. 1) features several important improvements with respect to "traditional" magnetic spectrometers devoted to hypernuclear studies: $\sim 3\pi\ sr$ solid angle coverage, momentum resolution for charged particle $\leq\ 0.5\%$, *neutron* detection capability, interaction vertex identification. These excellent performances, combined with the uniqueness of the DAΦNE K^- "source", would allow a significative breakthrough in our understanding of both strong and weak interactions.

2. Experimental results

During the first data-taking period (December 2003 - March 2004), we collected an integrated luminosity of $\sim 250\ pb^{-1}$, corresponding to $\sim 3 \times 10^7$ events due to hypernuclei production on targets of ^6Li, ^7Li, ^{12}C, ^{27}Al and ^{51}V. Actually this is the first, important result of the FINUDA experiment: we produced more Λ-hypernuclei than all the other experiments in 50 years, i.e. since the first Λ-hypernucleus identification [5].

Fig. 2 shows the display of a Λ-hypernucleus formation candidate event. The selection of such hypernuclear events proceeded through the following steps: first of all we looked

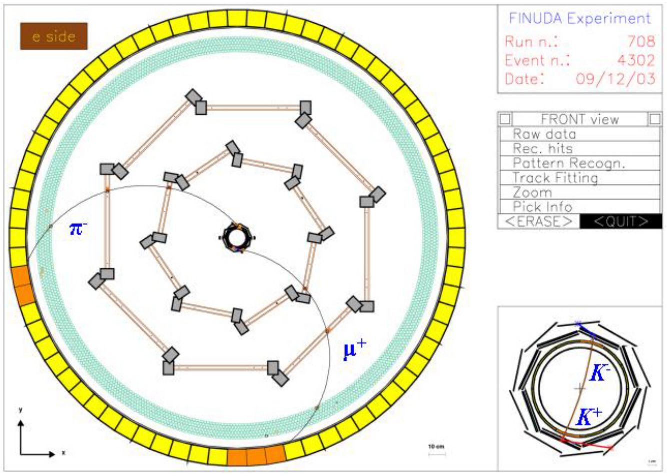

Figure 2. Display of a Λ-hypernucleus formation candidate event. A 260 $MeV/c\,\pi^-$, following the interaction of a K^- in the ^6Li target, and the μ^+, from the K^+ decay, are clearly visible; the inset shows a magnified view of the FINUDA central region with the reconstructed $K^\pm$ trajectories.

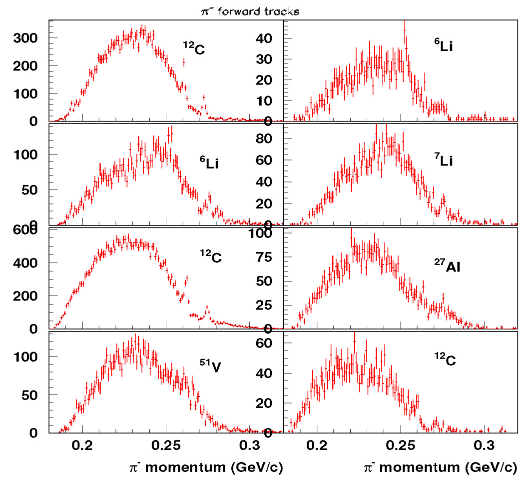

Figure 3. Reconstructed "forward" π^- momentum distribution for the 8 nuclear targets.

for a negative track, emerging from the K^- stopping point (π^- candidate); then we asked that these tracks crossed all the apparatus, so giving signal on all the 4 sub-detectors of the FINUDA spectrometer; among these tracks we retained only those entering the spectrometer without back-crossing the innermost part of the apparatus; finally we fitted these "forward" trajectories and we applied a correction to the reconstructed π^- momentum for the energy lost in the crossed materials. The final π^- momentum distributions for the 8 targets are reported in Fig. 3: in all spectra are visible some structures in the momentum range where the signals of hypernucleus formation are expected.

Being the most studied hypernucleus, $^{12}_{\Lambda}C$ represents the natural reference mark. For this reason we concentrated our initial efforts on the analysis of the data relative to one of the three ^{12}C targets ($\sim$ 20% of the available statistics on ^{12}C). Background reaction giving a π^- following K^--*nucleus* interactions were simulated for all the nuclear targets. These data samples were reconstructed and submitted to the same selection criteria as for the real events. The shape of the background π^- momentum distribution was parameterized and subtracted to the experimental one. The resulting spectrum, transformed now into the binding energy of the Λ, is shown in Fig. 4a): the two peaks at $B_\Lambda \simeq 11\ MeV$ and $0\ MeV$ correspond to the ground state (s_Λ) configuration and to the excited state of the $^{12}_{\Lambda}C$ with the Λ in the p-shell (p_Λ). This preliminary result was obtained with an energy resolution $\Delta E \simeq 1.4\ MeV$ ($\Delta p/p = 0.6$), about a factor 2 larger than the design one. It has to be considered as a fair starting value, that should improve after final calibration and overall detector alignment. Nevertheless the quality of our data is already comparable to present best world results: Fig. 4 shows the comparison

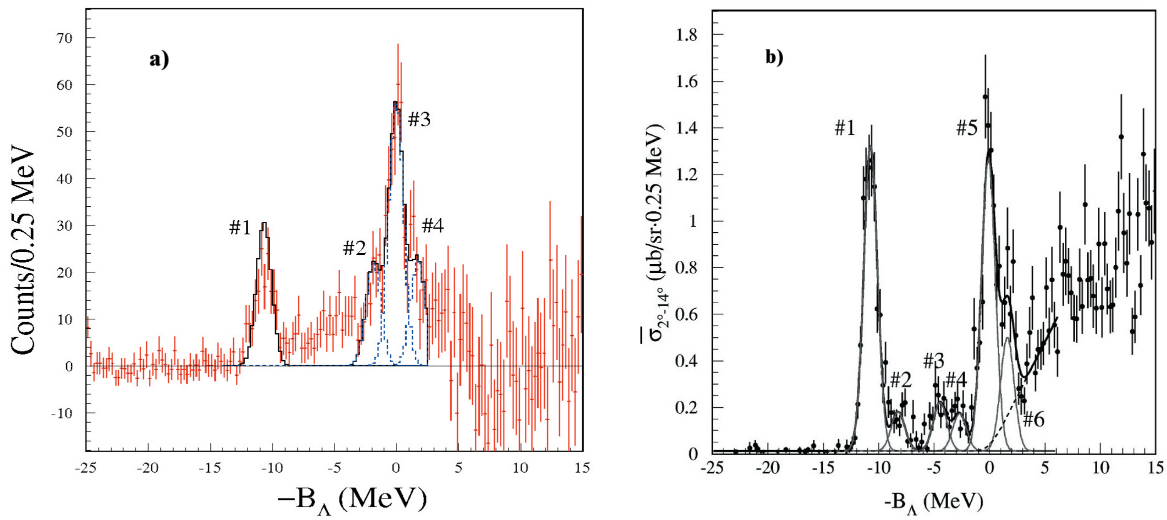

Figure 4. Comparison between ${}^{12}_{\Lambda}C$ mass spectrum obtained by the FINUDA (left) and E369 (right, from Ref. [6]) experiments. Only the statistical errors are reported in both cases.

between our spectrum and the one measured by the E369 Collaboration at KEK [6], with an energy resolution of $\simeq 1.5\ MeV$: peaks #1, #3 and #4 in Fig. 4a) are consistent with peaks #1, #5 and #6 of Fig. 4b), while peak #2 is not present in E369 data. However it is worth to remind that ${}^{12}_{\Lambda}C$ is produced via two different mechanisms: FINUDA exploits the (K^-_{stop}, π^-) strangeness exchange reaction, while E369 relies on the (π^+, K^+) associate production reaction. Hence the hypernuclear level population could be different in the two cases. The fit to our spectrum gave the following results:

Table 1
Preliminary results of the fitting to the ${}^{12}_{\Lambda}C$ spectrum. Only the statistical errors are quoted.

peak number	yield (events)	B_Λ $[MeV]$
1	185 ± 14	10.79 ± 0.04
2	131 ± 15	1.58 ± 0.09
3	338 ± 22	0.17 ± 0.06
4	131 ± 25	-1.99 ± 0.24

Finally we estimated a capture rate for ${}^{12}_{\Lambda}C$ of $\sim 1.8 \times 10^{-3}/K^-_{stop}$ for the g.s. and $\sim 3.3 \times 10^{-3}/K^-_{stop}$ for the p_Λ state.

Fig. 5 shows the energy distribution of the *proton* coming from the non-mesonic, proton-induced hypernucleus decay. This plot demonstrates the effectiveness of the FINUDA apparatus in detecting in coincidence the hypernucleus formation and the prongs following

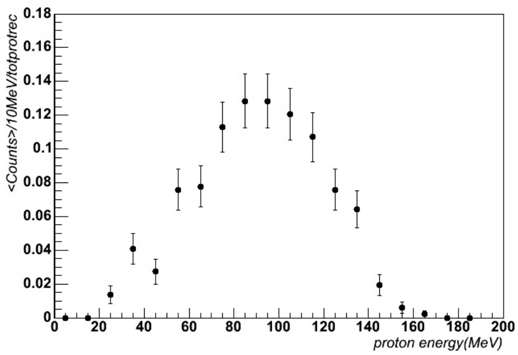

Figure 5. Energy distribution of *proton* from the non-mesonic decay of hypernuclei. The spectrum is not acceptance-corrected and it is normalized to the number of reconstructed *protons*.

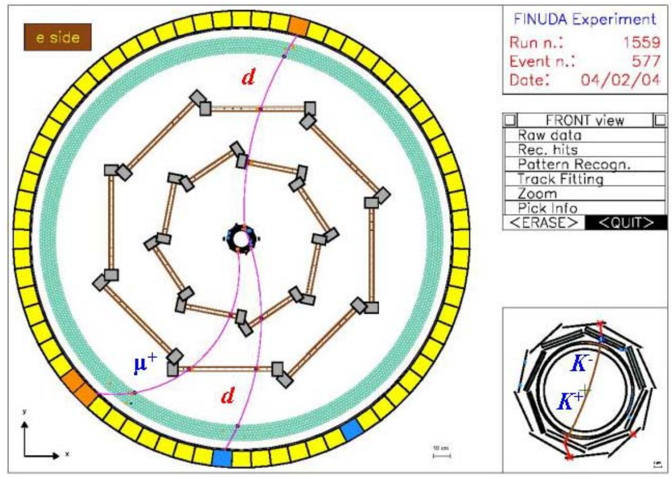

Figure 6. Display of a $^{4}_{\Lambda}He$ formation candidate event on a ^{6}Li target, followed by a decay into 2 *deuterons*. Besides the $\sim 570\ MeV/c$, highly ionizing tracks, it is also visible the μ^+, from the K^+ decay.

its decay. Thanks to this capability we looked also for some rare hypernuclear decays, like $^{4}_{\Lambda}He \rightarrow d + d$. Due to technical reasons we can use only solid nuclear targets. Then $^{4}_{\Lambda}He$ cannot be directly produced and we have to rely on the Coulomb assisted mechanism in order to produce it on heavier target (^{6}Li). The idea [7] is to recognize the $^{4}_{\Lambda}He$ formation by looking at some selected two-body, exclusive decay channels. Fig. 6 is the display of one of the 10 $^{4}_{\Lambda}He \rightarrow d + d$ events up to now identified.

In the last years nuclear matter characterized by large *neutron* to *proton* (N/Z) ratio attracted the attention of nuclear physicists.

It has been observed that in nuclear systems near the neutron drip line some of the nucleons moves far away from the nuclear core region. Majling pointed out [8] that Λ-hypernuclei could offer an even better playground to study this effect, the so called "halo phenomenon". Due to the fact that the Λ-hyperon have not to obey to the Pauli exclusion principle, an "extra binding energy" is available for a hypernu-

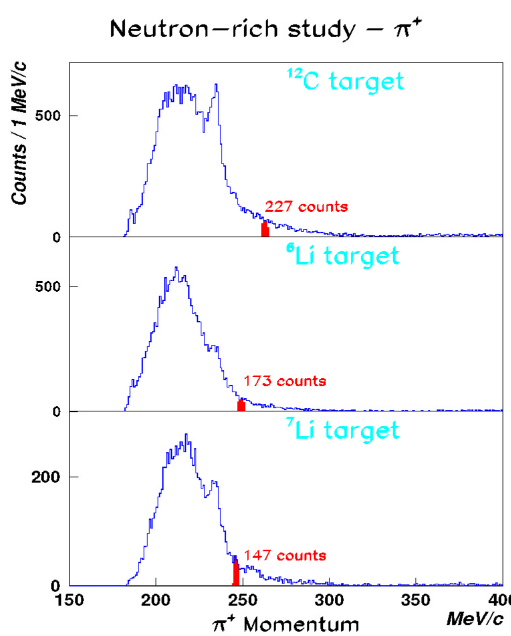

Figure 7: π^+ momentum distributions obtained from ^{12}C, ^{6}Li and ^{7}Li targets.

clear system: this way it is possible to form nuclear structure with extreme N/Z ratio ($[N/Z]_{hypernuclei} \simeq 2 \cdot [N/Z]_{ordinary\ nuclei}$). Up to now no experimental evidence of the existence of these objects have been found. With the FINUDA apparatus we looked for π^+s that represent the signature of a possible formation of neutron-rich hypernuclei via the two-step reaction (K^-_{stop}, π^+). Also in our case the search was apparently unfruitful: the π^+ momentum distributions (see Fig. 7) show in fact no evidence of peaks associated to the formation of such systems. Anyway from the number of reconstructed π^+ in the "region of interest" we were able to infer a preliminary upper limit for the neutron-rich hypernuclei formation at 90% C.L.: 2.1×10^{-5} for ${}^{12}_{\Lambda}Be$, 2.9×10^{-5} for ${}^{6}_{\Lambda}H$ and 4.3×10^{-5} for ${}^{7}_{\Lambda}H$. The first value improves the current limit obtained ak KEK [9], while the other two results represent the first estimation of the ${}^{6}_{\Lambda}H$ and ${}^{7}_{\Lambda}H$ production rate.

The data sample collected with the FINUDA apparatus offered the opportunity to address another interesting topic: the search for deeply-bound kaonic nuclei. The existence of such deeply bound states of a *kaon* in light nuclear system was proposed [10,11] in order to explain the experimental data on the $\overline{K}N$ scattering length, the kaonic Hydrogen (K^--p) atomic shift and the binding energy and the width of $\Lambda(1405)$. The idea [12] is to exploit the FINUDA capability to identify the Λ hyperon through its decay products. This way it is possible not only to tag the decay of deeply-bound states, but also to apply invariant mass spectroscopy [13] to directly search them. By looking at the $(K^-_{stop}, n$ or $p)$ reaction on different nuclear targets, we succeeded in observing the reaction $K^-pp \rightarrow \Lambda + p$ (or $\Sigma^0 + p$) by explicitly detecting a Λ and a *proton*, emitted back-to-back. The invariant mass distribution of the Λ-p system strongly suggests that the K^-pp system is characterized by a large amount of binding energy.

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