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FIRST HYPERNUCLEAR RESULTS FROM THE FINUDA EXPERIMENT AT DAΦNE

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Abstract

FINUDA is the hypernuclear physics experiment carried out at DAΦNE, the e^+e^-, ϕ-factory of the INFN Frascati Laboratory. The aim of the experiment is to study simultaneously the formation and decay of hypernuclei produced by the strangeness exchange reaction induced by the stopped K^- coming from the decay of the $\phi(1020)$ mesons. This paper presents the first preliminary results concerning spectrometer performances, hypernuclear formation and decay from the first FINUDA data set.

PACS: hypernucleus; spectroscopy

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1 Introduction

The Year 2003 has been an important year for Hypernuclear Physics: it was the $50^{\rm th}$ anniversary of the discovery, by Danysz and Pniewsky[1], of the first hypernucleus in an emulsion stack and FINUDA, the experiment designed for a complete study of hypernuclear production and decay, started successfully[2,3] its first data taking at DAΦNE.

An hypernucleus is a many-body system composed of conventional (non-strange) nucleons and one or more hyperons (Λ, Σ or Ξ). The presence of the strangeness degree of freedom in a hypernucleus adds a new dimension to the evolving picture of nuclear physics. A Λ particle embedded in a nucleus is stable against mesonic decay and strong interaction: hence it will survive for a while maintaining its own identity among other nucleons. In addition it can deeply penetrate inside the nucleus since the Pauli principle is not effective. Thus hypernuclei can provide invaluable information concerning the behavior of a baryon deep inside the nucleus and on the hyperon-nucleon interactions.

2 The FINUDA Experiment

FINUDA is an unconventional example of hypernuclear physics experiment, which is typically a fixed target experiment, carried out at a e^+e^- collider, the DAΦNE ϕ-factory[4].

The peculiar idea [5–7] of the FINUDA experiment is to stop the flux of slow and monochromatic K^- (127 MeV/c) coming from the main ϕ decay $\phi \rightarrow K^+K^-$ (49%) in thin nuclear targets ($0.1 \div 0.3\,{\rm g\,cm^{-2}}$) with minimum straggling. Thanks to the low momentum of the K^- only a few percent ($< 10\%$) of the produced K^- interact in flight while the remaining 90% is captured at rest (reversed percentages are possible with K^- produced at hadron machines). After degradation and nuclear capture, Λ-hypernuclei are produced through the reaction:

$$K^-_{stop} + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^- \tag{1}$$

and the spectroscopy of hypernuclear states can be performed by measuring the momentum of the isotropically emitted π^-. This feature provides unprecedented momentum resolution, as long as transparent detectors are employed before and after the target. A systematic survey of hypernuclear excitation covering the full A-range with a resolution better than 1 MeV is the goal of FINUDA which can also study[8] the weak decays of hypernuclei:

1. The mesonic decay favoured in the light hypernuclear systems,

$$\Lambda \rightarrow p + \pi^- \quad , \quad \Lambda \rightarrow n + \pi^o \tag{2}$$

2. When the Λ is embedded in medium-heavy ($A > 5$) nuclei, the mesonic decay (Eq. 2) is strongly suppressed [9] by phase-space reduction and by Pauli-blocking and new non-mesonic decay modes can take place:

$$\Lambda + p \rightarrow p + n \quad , \quad \Lambda + n \rightarrow n + n \quad , \quad \Lambda + N + N \rightarrow n + N + N \tag{3}$$

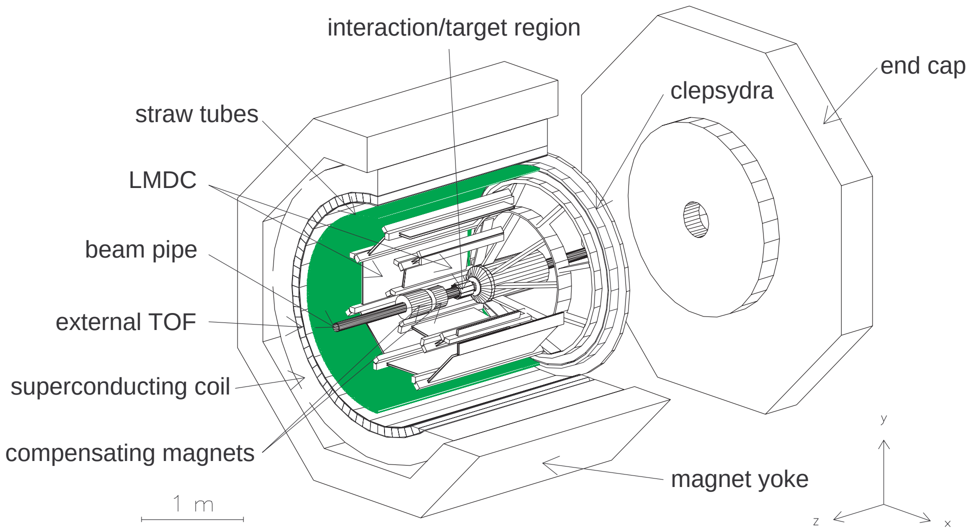

Figure 1: Layout of the FINUDA apparatus.

The weak hypernuclear decay modes are of great importance for the understanding of the baryon-baryon weak processes in nuclear matter[10–12].

2.1 The FINUDA apparatus

FINUDA is a magnetic spectrometer with the typical cylindrical geometry of collider experiments with high acceptance ($> 2\pi\,\mathrm{sr}$) and can provide high hypernuclear formation rates: 40 hypernuclei/hour at a luminosity of $5 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for a 10^{-3} capture rate.

The apparatus, described in detail in Ref. [6,7,13] and references therein, is sketched in fig. 1 and consists of an inner section surrounding the interaction region (beam pipe, thin scintillator counter barrel, 8-fold nuclear target, silicon microstrip detectors), an external tracker (low-mass planar drift chambers LMDC and a straw tube array detector), an outer scintillator array and a superconducting solenoid providing a magnetic field of 1.0 T. The whole tracking volume ($8\ \mathrm{m}^3$) is immersed in a He atmosphere to minimize Multiple Coulombian Scattering. The geometry of the spectrometer, the position of the detectors and the value of the maximum magnetic field have been optimized for maximizing the momentum resolution and acceptance for the prompt π^- from hypernuclear formation (Eq. 1). For such π^- (250-280 MeV/c), the design momentum resolution is $\Delta p/p = 3.5 \times 10^{-3}\,(FWHM)$, corresponding to a resolution of 830 keV in the hypernuclear energy levels.

3 The FINUDA Initial Physics Program

As already mentioned, the physics program of FINUDA aims at the simultaneous study of hypernuclear formation and decay. For the first data taking period the following targets have been used[14]:

- *A set of light targets:* two ^{6}Li and one ^{7}Li. The hypernucleus $^{6}_{\Lambda}Li$ is unstable for proton emission and it decays in 10^{22} s into $^{5}_{\Lambda}He + p$ or into hyperfragments $^{4}_{\Lambda}He + p + n$ and $^{4}_{\Lambda}H + p + p$ via the Coulomb assisted mechanism. The $^{5}_{\Lambda}He$ production can be identified by selecting the end-part of the momentum spectrum of the π^- from reaction 1. The $^{4}_{\Lambda}He$ hyperfragment can be recognized by its rare decay channel: $^{4}_{\Lambda}He \rightarrow d + d$ and $^{4}_{\Lambda}He \rightarrow p + H^3$ never seen before. Finally ^{6}Li target is interesting for the unexplored field of neutron-rich hypernuclei search[15].

  The low-lying excited spectrum of $^{7}_{\Lambda}Li$ is the most extensively studied with high resolution γ spectroscopy[16] but its mesonic decay variables can be measured for the first time.

- *A set of three targets of* ^{12}C. The best known hypernucleus is $^{12}_{\Lambda}C$, having been recently studied at KEK with 1.45 MeV FWHM resolution[17]. For this reason it can be used as a reference nucleus by FINUDA and at the same time the precision on the measured observables will be improved.

- *A set of medium-heavy targets*: one ^{27}Al and one ^{51}V. Apart from an old measurement with K^- in flight[18] with a coarse resolution of 6 MeV FWHM, no other data were produced for $^{27}_{\Lambda}Al$. Therefore it is very interesting to measure its excitation spectrum and its ground state capture rate. The excitation spectrum of $^{51}_{\Lambda}V$ was measured at KEK with an energy resolution of 1.65 MeV[19]and peaks corresponding to the p and d single-particle orbits show possible splitting, which have been tentatively attributed to a non-zero value of the Λ spin-orbit potential. The ultimate energy resolution of FINUDA would shed light on this important issue. The measurement of the ground state formation capture rate in K^-_{stop} for medium-heavy nuclei can be accomplished for the first time.

4 FINUDA Performances During the First Data Taking Run

After a short commissioning of the collider and of the apparatus started in mid October 2003, the first FINUDA data taking started on December 1^{st} 2003 and lasted till March 22, 2004. DAΦNE delivered in total an integrated luminosity of $250\mathrm{pb}^{-1}$, of which 33 were used for machine tuning, 10 for FINUDA detector debug, the useful data correspond to $190\mathrm{pb}^{-1}$ excluding data-taking dead-time. The maximum daily integrated luminosity delivered to FINUDA was $4.0\mathrm{pb}^{-1}$, with a maximum peak instantaneous luminosity of $6 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The first events triggered by FINUDA were Bhabha events, i.e. $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow e^+e^- + \gamma$, useful for in-beam calibration of the detectors and for luminosity evaluation. The e^+e^- invariant mass is shown in Fig.2: the beam energy (1020 MeV) peak is clearly seen together with a peak due to $K_S \rightarrow \pi^+\pi^-$ (from $\phi \rightarrow K_S K_L$) (recorded in the Bhabha trigger), while the small bump on the right of the K_S peak corresponds to the decay of the $\rho^0(770) \rightarrow \pi^+\pi^-$ coming from the $\phi \rightarrow \rho^0\pi^0$ decay.

In fig.2 is also shown the momentum distribution of positive tracks coming from the K^+ stopping points: the two peaks at 236 MeV/c and 205 MeV/c correspond respectively to the two-body decays $K^+ \rightarrow \mu^+\nu_\mu$ and $K^+ \rightarrow \pi^+\pi^o$. From the width of the μ^+ peak the momentum resolution of the apparatus can be

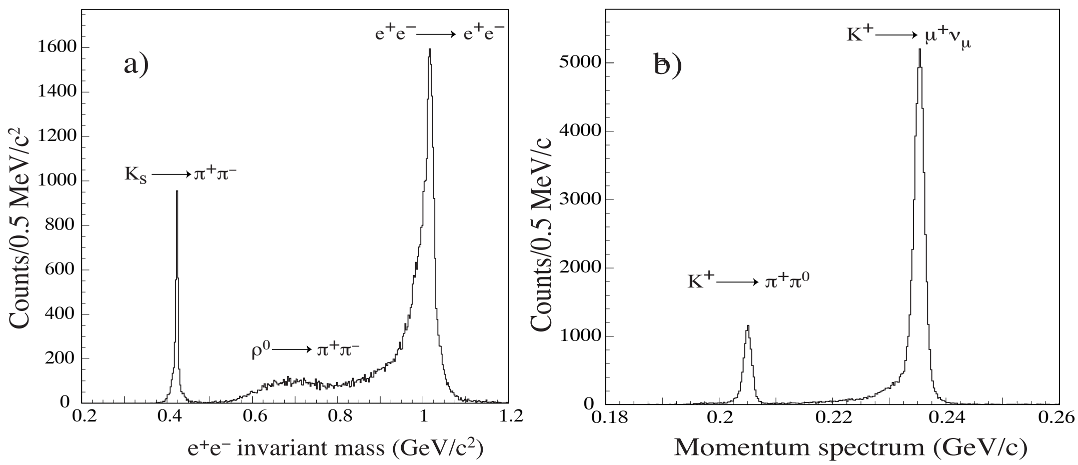

Figure 2: a) Reconstructed invariant mass of the e^+e^- system with the peak at 1020 MeV (see details in the text). b) Reconstructed momentum distribution of the positive particles coming from the decay of positive kaons.

estimated as $\Delta \mathrm{p}/\mathrm{p} = 0.9\%\mathrm{FWHM}$. This has to be considered as a fair starting value that should improve to the design value after final calibration and detector alignment.

The trigger selecting hypernuclear formation events[7] requires two back-to-back slabs firing on the inner scintillator barrel (above an energy threshold accounting for the high ionization of slow kaons) and a fast coincidence on the outer scintillator barrel. A typical candidate for a hypernucleus formation event is shown in Fig.3, with superimposed the reconstructed tracks exiting from the interaction region: the μ^+ from the K^+ decay and a 260 $\mathrm{MeV/c}$ negative pion from the hypernucleus formation on a ^6Li target.

The reconstructed y vs x coordinates of the K^- stopping points on the targets are shown in the scatter-plots of in Fig.4. In the first plot all the reconstructed K^-_{stop} are shown, in the second one only the eight nuclear target stopping points are selected, in the third plot only the stopping points in the silicon μ-strip detector are shown, in the last one the remaining points stopping in other volumes. The left/right asymmetry in the accumulation of points is due to the (e^+, e^-) crossing angle of 12.5 mrad that determines a small total momentum of about 12.8 MeV/c of the generated ϕ in the positive x-direction (beam-boost).

5 First Preliminary Results on $^{12}_{\Lambda}C$ Hypernuclear Spectroscopy

The sample of 3×10^7 collected events has been processed by the FINUDA reconstruction program, which selects hypernuclear candidate events for the formation of hypernuclei, and reconstructs the tracks fitted parameters. The following requirements were applied to the selected candidates:

- a negative track from a K^- (pion candidate),
- a fitted track with 4 points in the spectrometer,
- a forward track, i.e. not crossing back the interaction/vertex region,

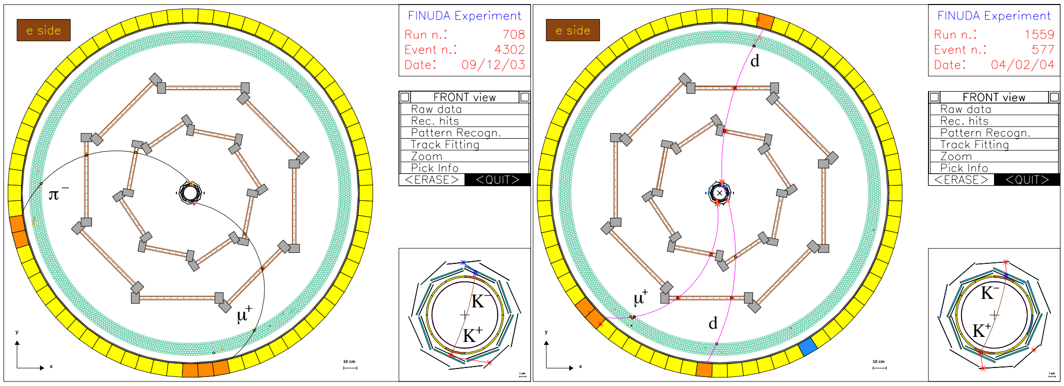

Figure 3: Left: display of a hypernucleus formation event with reconstructed μ^+ and π^- tracks. Right: candidate event for the rare non mesonic decay ${}^4_\Lambda He \rightarrow d + d$. The two deuterons come from the K^- vertex, a μ^+ from K^+ decay. Enlarged views of the vertex region with the (K^+, K^-) trajectories are shown in the insets.

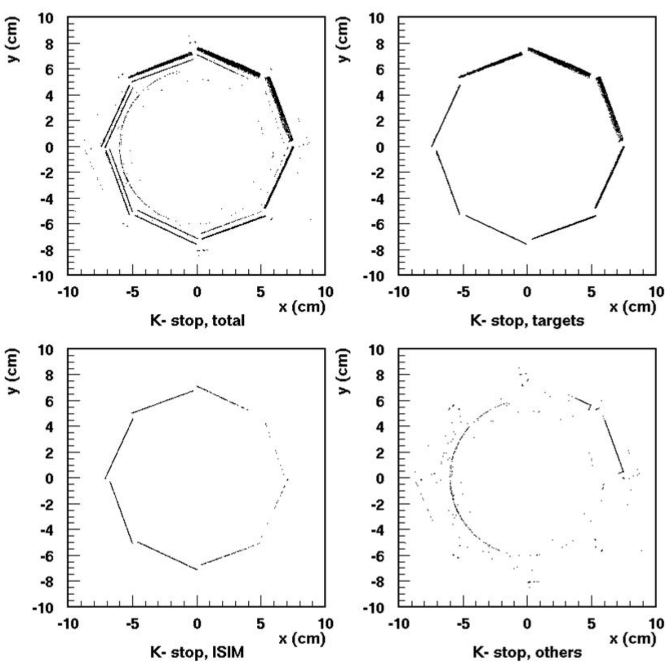

Figure 4: Scatter plot of the reconstructed y vs x coordinates of the K^- stopping points in the target/interaction region. See details in the text.

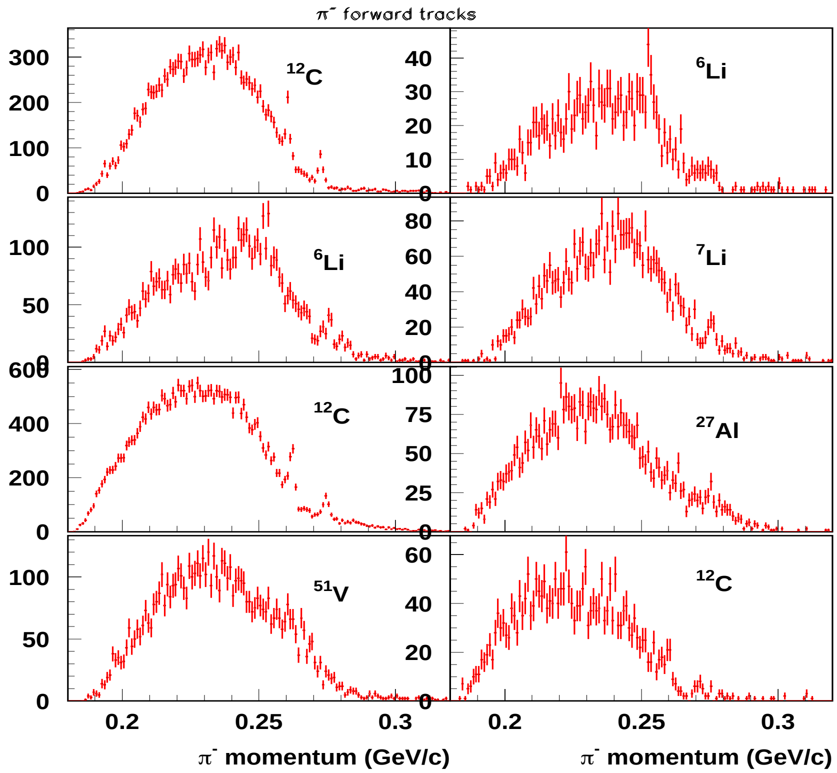

Figure 5: Distribution of the momentum of the selected forward pions on the 8 nuclear targets. Clear hypernuclear peaks can be already seen.

- the particle momentum reconstructed corrected for the energy loss in the crossed materials,
- quality cuts on track fitting.

In Fig.5 the momentum distribution for the selected π^- in the eight targets is shown, where clean hypernuclear structures appear in the expected momentum range. All the cuts above mentioned have been chosen by varying them in order to obtain the best signal-to noise-ratio, with no detailed optimization studies being done yet. We start with the detailed study of the $^{12}_{\Lambda}C$ hypernucleus, which can be used as a reference being the best known hypernucleus. In the following we refer to ^{12}C target number one (about 20% of the available statistics on ^{12}C).

Background reactions giving a π^- following K^--nucleus interactions have been simulated for all the nuclear targets. The simulated background events have been reconstructed and π^- selected following the same selection criteria as for the hypernucleus formation candidates. The measured momentum spectrum, both for the ^{12}C candidates and for the background reaction is transformed into the binding energy of the Λ: $B_\Lambda = M_{A-1} + M_\Lambda - M_A - M_K + M_\pi + T_\pi$, where M_{A-1} is the mass of the core nucleus at its ground state, M_A is the mass of the target nucleus, M_Λ is the mass of the Λ hyperon, and M_π, T_π are the mass

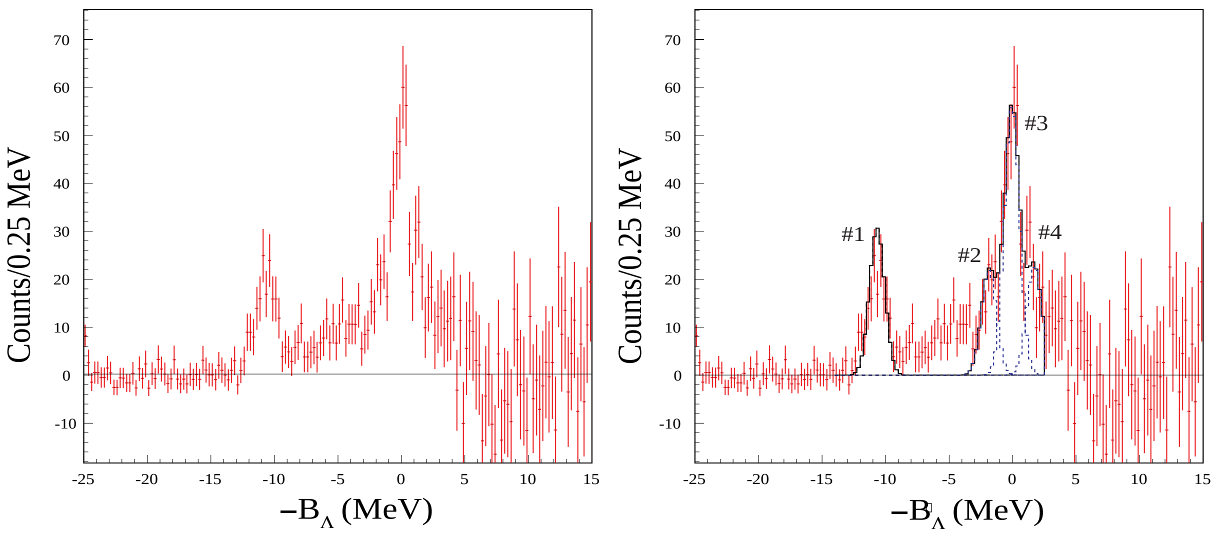

Figure 6: Preliminary ^{12}C hypernuclear mass spectrum after background subtraction with (right) and without (left) fitting curve described in the text.

and kinetic energy of the prompt pion. Hence the shape of the background spectrum is parameterized and subtracted from the experimental one. The obtained distribution is shown in Fig.6: two prominent 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 $^{12}_{\Lambda}C$ hypernucleus with the Λ in the p-shell (p_Λ). The spectrum has been fitted with four Gaussian peaks, one for the ground state and three for the excited state, after having excluded the region between the two main peaks due to the low statistical significance in this region. The energy resolution has been set at $\sigma_E = 600$ keV (that is $\Delta E = 1.45$ MeV, $\Delta p/p = 0.6\%$), given by the peak at $B_\Lambda = 0$. In the fit the gaussian widths were constrained to be the same and equal to σ_E. The results of the fit are summarized in Table 1.

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

Peak number	Yield (events)	B$_\Lambda$ (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

The capture rate for $^{12}_{\Lambda}C$ formation can be estimated to be $1.8 \times 10^{-3}/K^-_{stop}$ for the ground state and $3.3 \times 10^{-3}/K^-_{stop}$ for the p_Λ state.

The FINUDA preliminary result on $^{12}_{\Lambda}C$ can be compared with the result of previous experiment KEK-E369[17]: peaks $\#1$, $\#3$ and $\#4$ are consistent with E369 while peak $\#2$ was not evident. The structure in the region between the two peaks will be investigated soon with the whole statistics on ^{12}C. The quality of FINUDA data is already comparable to present best world result.

6 Preliminary Results on Rare Weak Decays, Neutron-Rich Hypernuclei and Σ Bound States Searches

A search for rare non mesonic decay of ${}^{4}_{\Lambda}He$ using the ${}^{6}Li$ target is being carried out and the rare decay channel ${}^{4}_{\Lambda}He \rightarrow d + d$, never observed before, can be searched for. At present 10 candidate events for the above reaction, with the deuteron momentum in the expected region of $570\ \mathrm{MeV/c}$ have been found, one candidate is shown in Fig.3.

The existence of hypernuclei with a large neutron excess ($N/Z_{HYP} \sim 2N/Z_{ordinarynuclei}$) has been theoretically predicted [20] but not yet observed. The Λ hyperon does not suffer the Pauli principle constraints. This produces an "extra binding energy" and a larger number of neutrons may be bound with respect to ordinary nuclei.

The global production reactions respectively on ${}^{12}C$, ${}^{6}Li$, ${}^{7}Li$ are :

$$K^{-}_{stop} +^{12} C \rightarrow \ {}^{12}_{\Lambda}Be + \pi^{+} \quad (N/Z) = 2$$

$$K^{-}_{stop} +^{6} Li \rightarrow \ {}^{6}_{\Lambda}H + \pi^{+} \quad (N/Z) = 5$$

$$K^{-}_{stop} +^{7} Li \rightarrow \ {}^{7}_{\Lambda}H + \pi^{+} \quad (N/Z) = 6$$

The momentum distribution for the π^{+} candidate neutron-rich events are shown in Fig.7. At the moment there is no evidence of peaks associated to the searched states, but from the counts of N_{π} (indicated in the picture), it is possible to evaluate a preliminary experimental upper limits for the Neutron-rich hypernuclei formation at 90% C.L.: 2.1×10^{-5} for ${}^{12}_{\Lambda}Be$, 2.9×10^{-5} for ${}^{6}_{\Lambda}H$, 4.3×10^{-5} for ${}^{7}_{\Lambda}H$. The result for ${}^{12}_{\Lambda}Be$ already improves previous KEK result[21], while for ${}^{6}_{\Lambda}H$ and ${}^{7}_{\Lambda}H$ this is the first search of such hypernuclei. For a detailed description of this analysis see Ref.[22].

Σ-hypernuclei (bound states of a Σ hyperon inside a nucleus) are not expected to exist but experimental evidence of ${}^{9}_{\Sigma}Be$, ${}^{12}_{\Sigma}C$, ${}^{12}_{\Sigma}Be$ was first claimed[23] and later disclaimed[24]. Only one ${}^{4}_{\Sigma}He$ has been definitely observed[25], it may be considered an exception connected to the special structure of this system, anyhow the enigma of the existence of Σ-hypernuclei remains open. FINUDA can contribute to the experimental study of possible Σ-bound states in the $(K^{-}_{stop}, \pi^{-,+})$ thanks to its tracking capability. In Ref.[22] are exposed the details of the preliminary analysis of FINUDA data that has yield the candidates of Fig.7, showing positive expectations for Σ-bound states in the region beyond $\mathrm{A} = 4$.

7 Conclusions and Future Prospects

FINUDA has successfully ended its first data taking collecting 3×10^{7} events. Preliminary results in hypernuclear spectroscopy of ${}^{12}_{\Lambda}C$ with partial statistics and not yet final momentum resolution already show a quality comparable to the present world results. Preliminary results on other hypernuclear physics items such as hypernuclear decays and rare decays, neutron-rich hypernuclei, search for Σ-bound states show interesting hints for further analysis and data taking. These results should improve significantly with progress in data analysis after final detector alignment and calibration, improvements in track fitting, etc.

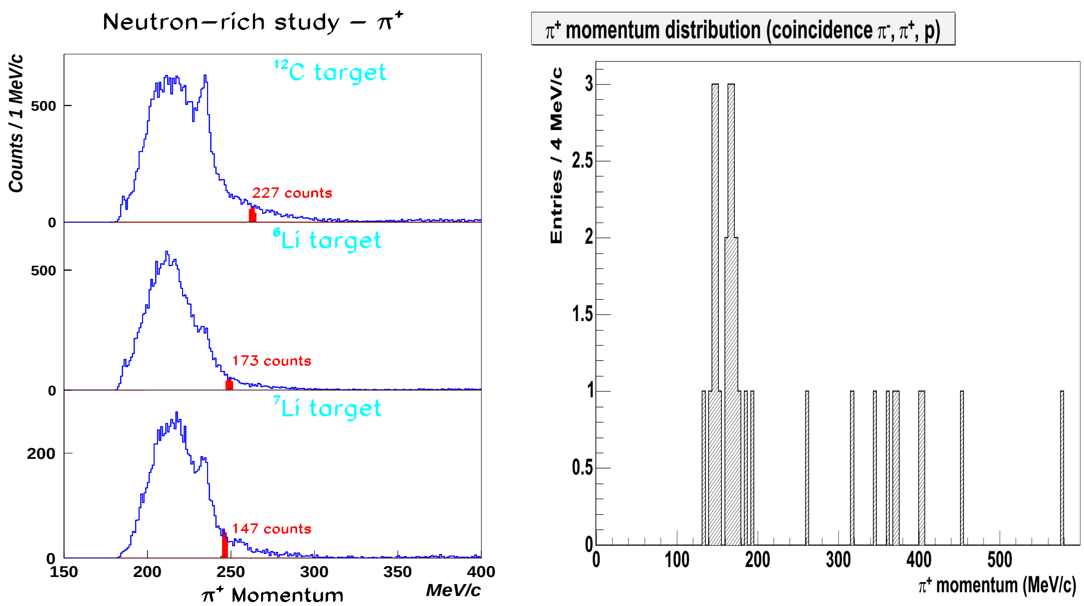

Figure 7: Left: momentum distribution of π^+ candidate events from the formation of neutron-rich hypernuclei. Counts of interesting events in the expected regions are shown. Right: momentum distribution of π^+ from $^{12}_{\Sigma}Be$ candidates events.

For the next data taking in 2005 two options are foreseen for the FINUDA physics program, depending on the final results of the present data: either a full assembly of ^6Li, ^7Li targets to study the rich physics of rare decays and deeply bound K^- states or an assembly of four pairs of heavy targets for hypernuclear spectroscopy and decay studies.

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