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FINUDA: a hypernuclear factory

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Abstract. FINUDA (FIsica NUcleare a DAΦNE) is a hypernuclear physics experiment carried out at the DAΦNE e^+e^- Φ-factory at the Frascati INFN laboratory. FINUDA is the first experiment producing hypernuclear states by stopping the low energy negative kaons, arising from the Φ decay, inside different nuclear targets. The detector is a cylindrical magnetic spectrometer optimized to have the maximum momentum resolution and acceptance for the prompt π^- from Λ-hypernucleus formation, but it can also detect Λ decay particles, or the other kaon-nucleus interaction products. The first FINUDA data taking took place from October 2003 to March 2004. This work briefly summarizes the main results of the analyzes carried out, and describes the plans of the new data taking started October 2006.

PACS. 21.80.+a Hypernuclei – 13.75.Ev Hyperon-nucleon interactions

1 Introduction

FINUDA is an international collaboration of 12 institutes from 5 countries, with the aim of studying hypernuclear physics. Hypernuclei are produced via the reaction:

$$K^- +^A Z \rightarrow^A_\Lambda Z + \pi^- \tag{1}$$

stopping K^- from $\Phi(1020)$ decay into thin (0.21 - 0.38 g cm^{-2}) nuclear targets. The spectroscopy of the hypernuclear levels produced is performed by measuring the momentum of the outgoing π^-, but also the products of the sub-sequent decay of the Λ embedded in the nucleus can be detected allowing to investigate the decay mechanisms of hypernuclei at the same time. For this purpose, a cylindrical magnetic spectrometer has been constructed, and presently it is taking data at the DAΦNE collider [1]. In the following sections the main features of the FINUDA spectrometer and of the DAΦNE machine will be illustrated together with the main scientific results obtained so far analyzing the first 200 pb^{-1} collected from October 2003 to March 2004.

2 The DAΦNE collider

DAΦNE is an e^+e^- Φ-factory under operation at the Frascati National Laboratory of INFN since 1998. The electron and positron DAΦNE beams may collide in two opposite interaction points located in the two straight sections of the machine, where the experimental apparata are installed. They have an energy of 510 MeV and collide with an angle of about 25 mrad. Thus the Φ resonance is not produced at rest, but with a small momentum (boost) of about 12.3 MeV/c toward the positive direction of the x axis (see fig. 4 for the definition of the reference frame). A schematic layout of DAΦNE machine can be seen in fig. 1. The Φ resonance so produced decays with a BR = 0.49 to K^+, K^- pairs, and these K^- are used by FINUDA as a beam to perform physics studies. Fig. 2 shows the measured stopping points of the negative kaons arising from Φ decay inside the FINUDA spectrometer. The Φ boost direction is also shown. The small momentum of the Φ affects also the momenta of the K^+, K^- produced in the decay. In fact, if the Φ decay occurred at rest, the kaon's momentum would be 127 MeV/c, independently

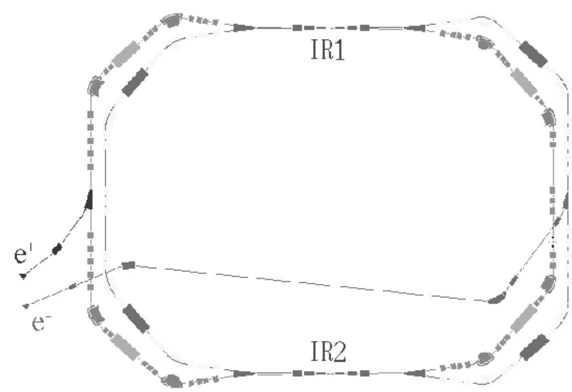

Fig. 1. Schematic layout of DAΦNE collider.

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from their direction, and their angular distribution would be symmetric around the beam axis. Due to the boost, the momentum of the kaons depend on the azimuthal angle of emission being slightly larger in the boost direction, and smaller on the opposite side. Moreover, the kaon emission distribution is no longer symmetric.

The main DAΦNE design parameters are reported in tab. 1.

Table 1. DAΦNE machine main design parameters.

beam energy	510 MeV
design luminosity	$5{\cdot}10^{32}$ cm^{-2}s^{-1}
σ_x,σ_y,σ_z (rms)	2.11 mm, 0.021 mm, 35 mm
bunch length	30 mm
crossing angle	12.5 mrad
max frequency	368.25 MHz
bunch/ring	up to 120
part./bunch	8.9 10^{10}
max current/ring	5.2 A

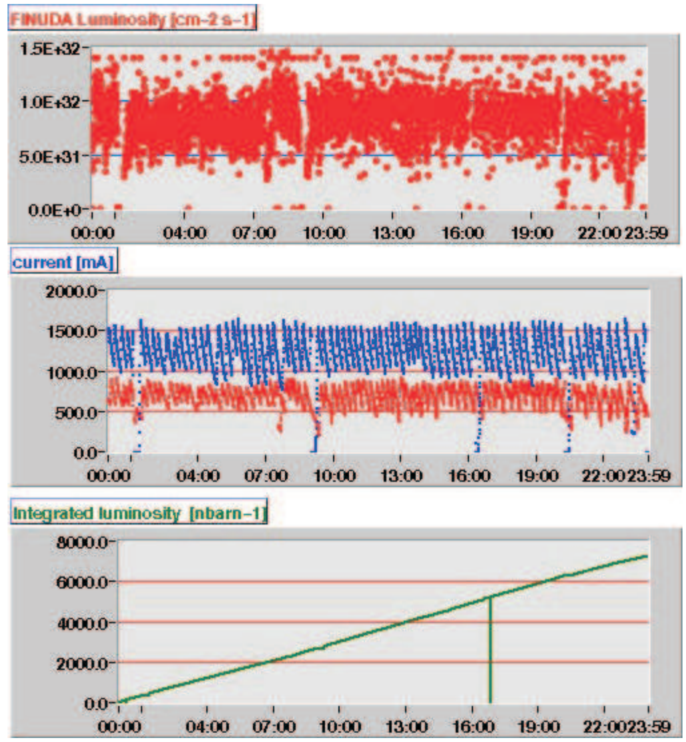

Fig. 3. DAΦNE collider average performance along 24 hours. (top) Instant luminosity evaluated by FINUDA. (middle) Electron and positron currents. (down) Daily integrated luminosity.

Presently DAΦNE is running with a top luminosity of about $1{\times}10^{32}$ cm $^{-2}$ s^{-1} delivering to the FINUDA experiment about 5 pb $^{-1}$ per day (fig. 3).

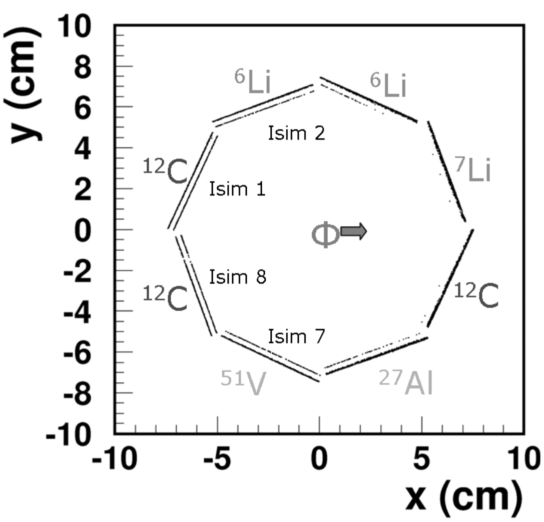

Fig. 2. Stopping points of the negative kaons from Φ decay inside the FINUDA interaction/target region. The Φ boost direction is also indicated by the central arrow. The target layout is that of the first data taking.

More details on DAΦNE machine can be found in [2].

3 The FINUDA spectrometer

The FINUDA spectrometer is housed inside a non-focusing, superconducting solenoid (B = 1.0 T; $\emptyset$ = 240 cm) located around the thin (500 μm; $\emptyset$ = 10 cm) Be beam pipe of DAΦNE. It consists of several arrays of tracking detectors and of two scintillator barrels arranged around the beam axis. The innermost scintillator barrel (TOFINO) is placed just around the beam pipe, and it is made of 12 thin (thickness 1.8 mm, length 20 cm) scintillator slabs. The outer barrel (TOFONE) is composed by 72 thick scintillators (thickness 10 cm, length 255 cm) and it is fixed to the iron yoke of the FINUDA magnet. The two scintillator barrels are used for trigger purposes, and for Time Of Flight (TOF) measurements. TOFONE detects also neutrons with an efficiency of about 11%.

After the first round of data taking, TOFINO has been completely re-build with new thinner scintillators. The previously used Hybrid Photo Diode devices have been replaced with Hamamatsu R5505 photomultipliers, which can work with good gain and low noise inside magnetic fields. Furthermore, new lower walk constant fraction discriminators have been adopted to shape the analog signals. These changes have improved the time resolution of TOFINO that now is about 250 ps FWHM.

The FINUDA apparatus can be logically divided into two areas: the interaction/target region, and the outer tracking zone. The interaction/target region consist of TOFINO barrel, and of a set of eight thin (about 200 mg/cm^2) nuclear targets installed between two arrays of bi-dimensional Si micro-strip detectors, 400 μm thick and 20 cm long. The internal array (ISIM) allows to measure the crossing point of the K^- (K^+) coming from the Φ decay, while the external array (OSIM) measures the crossing points of the outgoing charged particles resulting from kaon target interactions. The Si micro-strip detectors also perform dE/dx measurements providing good particle identification [3].

Charged particles tracking is performed by means of two co-axial octagonal layers of Low Mass Drift Chambers (LMDC) [4] followed by six layers of thin-walled Straw Tubes (ST) [5]. The first two straw layers are parallel to the detector axis, the others have a skew angle of $\pm 15^o$ to allow the evaluation of the z-coordinate. The whole FINUDA tracking volume is filled with Helium, in order to minimize the effect of the multiple Coulomb scattering of low momentum particles, which deteriorates the best achievable momentum resolution. A sketch of the FINUDA apparatus is visible in fig. 4.

The first level trigger of the FINUDA apparatus is based on the fast signals coming from TOFINO and TOFONE properly combined in order to recognize defined hit topologies, and energy deposition in the scintillator slabs. In particular, the latter condition is necessary to select highly ionizing particles, namely the low energy kaons, against the minimum ionizing ones. The two basic triggers used during the data taking are: Bhabha trigger and Hypernuclear trigger. The first one is meant to select Bhabha scattering events ($e^+e^- \to e^+e^-$) which are necessary to monitor the machine performance, and to check detector functioning. It requires only two back-to-back hits in TOFINO with an energy deposition below kaon threshold, and a multiplicity on TOFONE in the range 2 to 8. The Hypernuclear trigger requires two back-to-back hits on TOFINO above the kaon energy thresholds, but without imposing multiplicity two on the internal scintillator barrel. In fact, the products of K^- interaction with the target may be emitted backward re-hitting the TOFINO detector. On TOFONE, hypernuclear trigger asks for a multiplicity in the range 2 to 8.

At present FINUDA detector is taking data with the following targets: 2 ^{6}Li, 2 ^{7}Li, 2 ^{9}Be, 1 ^{13}C, and 1 of deuterated water. The choice focuses on medium-light nuclei which offer the opportunity of studying a wider scientific program:

- hypernuclear spectroscopy and decay;
- search for di- and tri-baryons kaon-nucleon systems;
- neutron rich hypernuclei;
- K^+N charge exchange reaction.

In the following section more details on this program will be given.

4 The FINUDA scientific program

FINUDA research program is extremely wide and spans over the search for deeply bound kaon-nuclear states, the study of Λ-hypernuclei production, spectroscopy and decay, the investigation of neutron rich hypernuclei existence, and the search for Σ-hypernuclei. In all these fields FINUDA has been able to produce high quality results. In the following sub-sections I'll make a review of what FINUDA has already find out, pointing out which improvements could be expected with the new high statistics data set.

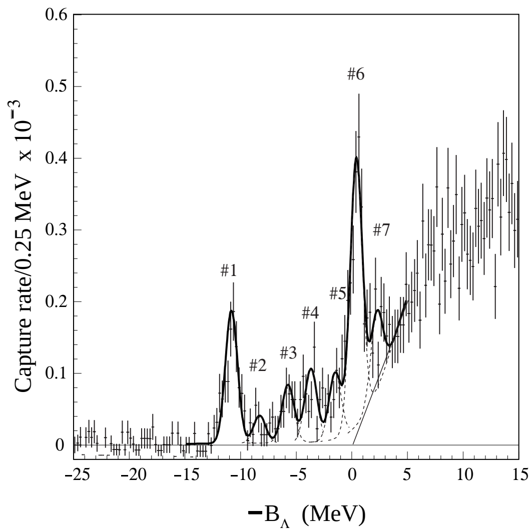

Fig. 5. $^{12}_{\Lambda}$C hypernuclear spectrum measured by FINUDA.

4.1 Hypernuclear Physics

The spectroscopy of Λ-hypernuclei has been a powerful tool to study ΛN interaction instead of difficult and low statistic ΛN scattering experiments. This field received a boost with the production of high precision data coming from Ge-detectors experiments measuring γ-ray transitions of hypernuclear levels. Thanks to that, ΛN spin-dependent contributions to the interaction are finally being measured.

FINUDA cannot compete with these measurements, but can produce complementary information by combining the spectroscopic studies to the investigation of the decay modes of hypernuclear states. With the first set of acquired data, FINUDA produced good results in this field for $^{12}_{\Lambda}$C, $^{7}_{\Lambda}$Li, hypernuclear systems. The detailed descriptions of the analyzes performed, and of the obtained results can be found elsewhere in these proceedings [7,8].

Figures 5 and 6 illustrates $^{12}_{\Lambda}$C and $^{7}_{\Lambda}$Li hypernuclear spectra respectively. The spectrum of $^{12}_{\Lambda}$C [9] closely resembles that measured by E369 experiment [10]. This is expected, as the production of hypernuclear states is, in first approximation, determined by the momentum transferred to the Λ, which, for both experiments, is grossly comparable ($\sim$ 250 MeV/c for FINUDA, $\sim$ 350 MeV/c for E369). The use of Carbon targets during the first data taking was essentials meant for testing the detector capabilities on a well known hypernuclear system. The good quality of FINUDA data is evident, and even the improvements with respect to the previous similar experiments. The energy resolution of our spectrometer finally turns out to be 1.1 MeV.

Figure 6 shows $^{7}_{\Lambda}$Li hypernuclear spectrum. This is one of the most studied hypernuclei not only in formation experiment. Recently, the experiments E419 at KEK and E930 at BNL by using a large acceptance Germanium array (Hyperball) performed high resolution spectroscopy of $^{7}_{\Lambda}$Li, defining precisely the level scheme and the energies of the bound states [11]. Regarding the two levels identified

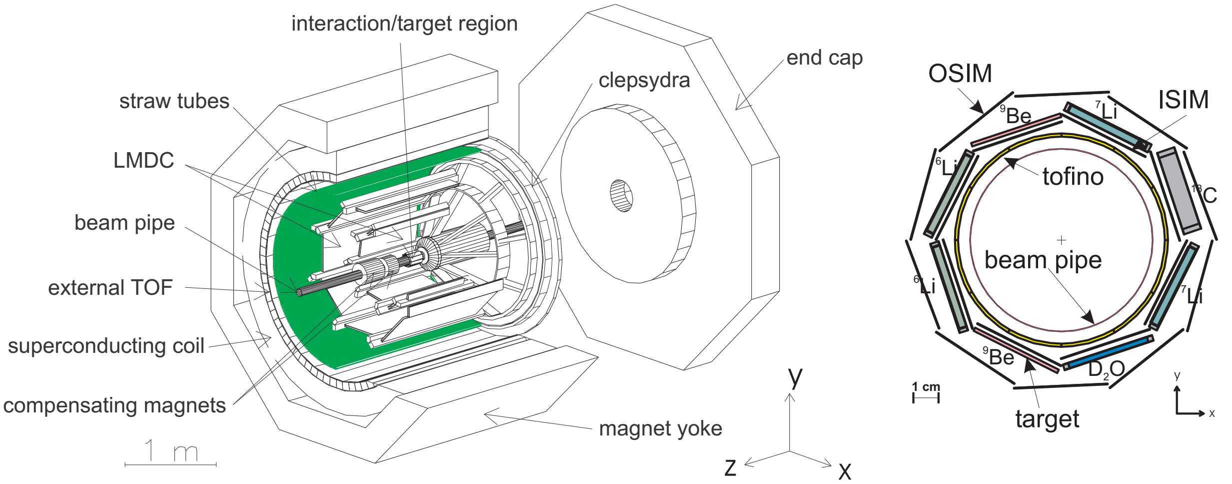

Fig. 4. Layout of the FINUDA apparatus (left). Detail of the interaction/target region (right).

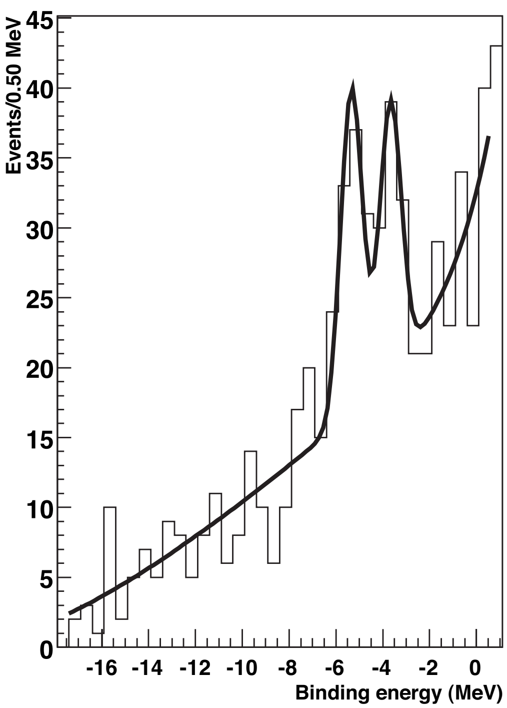

Fig. 6. ${}^{7}_{\Lambda}$Li hypernuclear spectrum measured by FINUDA.

by our analysis, we have tried to place them in the level scheme determined with the Hyperball. The first (left) peak could be a mixture of the ground state with the first excited state ($3/2^+$) since the value of the energy is laying in between the two. In the same way, the second (right) peak can be the $5/2^+$ state, or the $7/2^+$ state or a mixture of the two.

Concerning the decay of Λ hypernuclei, the scarce statistics collected so far allows only to attack the investigation of ${}^{12}_{\Lambda}$C since 3 carbon targets were mounted inside the spectrometer during the first data taking. The FINUDA spectrum of protons from non-mesonic weak-decay ($\Lambda n \rightarrow np$) is reported in fig. 7. The proton energy distribution is centered around 80 MeV with a width of $\sim$ 60 MeV, corresponding to the Q-value of the weak reaction widened by the Fermi momentum of the interacting nucleon. The low energy rise, is probably due to Final State Interactions of the outgoing particles and/or to the contribution of the two nucleon induced reaction $\Lambda(np) \rightarrow nnp$. The shape of the distribution is also consistent with early theoretical works [12]. However, the comparison with an high statistic similar spectrum measured at KEK by E462/E508 experiments [13] shows some differences. The scenario will be better understood with new high statistics easements [7].

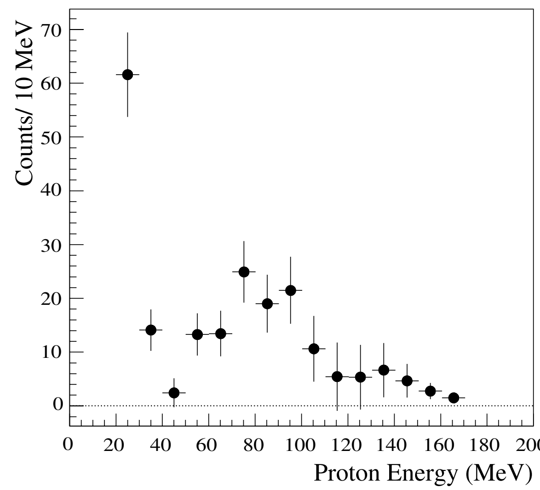

Fig. 7. Energy spectrum of the protons from non-mesonic weak-decay of ${}^{12}_{\Lambda}$C hypernucleus

A K^- impinging on a nucleus can even produce Σ hyperons, but unlike the case of Λ particle that is stable toward the strong interaction, the Σ can undergo, with high probability, the reaction $\Sigma N \rightarrow \Lambda N$ which then prevents the formation of Σ-nucleus bound states. Nevertheless, at least one Σ hypernucleus has been experimentally identified: (${}^{4}_{\Sigma}$He) [14]. This unexpected results was theoretically explained with a repulsive ΣA potential at short distances

[15] which can contrast the absorptive $\Sigma N \to \Lambda N$ conversion reaction, together with a strong isospin dependence of the Σ-nucleus potential. Whether Σ-bound states exist on heavier nuclei is still controversial, and this is due to the poor knowledge of Σ-nucleus potential. Nevertheless, such states could be experimentally detectable only if some mechanism can suppress the strong Σ absorption inside the nuclear matter.

In FINUDA Σ hypernuclei search is performed by studying

$$K^-_{stop} + ^A Z \to ^A_{\Sigma^{\pm,0}} Z' + \pi^{\mp} \quad (2)$$

The Σ hyperon then convert into a Λ via the already mentioned strong reaction, and generally has enough momentum to escape from the nucleus and to decay in the free space. The strategy for detecting such events is that to identify a prompt π signaling the formation of the hypernucleus, in coincidence with a π^-, p pair coming from a secondary vertex and giving the invariant mass of a Λ. The results of the analyzes performed are the subject of N. Grion's talk at this conference.

4.2 Nuclear bound kaonic systems

The search for nuclear bound kaonic systems was not included in the original scientific program of FINUDA. Nevertheless, the detector characteristics have turned out to be excellent to give clear results on a topic that has became of extreme interest in the last years. In fact, the existence of kaon-nucleon bound systems is not accepted world-wide. The main features of $\bar{K}N$ and $\bar{K}A$ interactions don't foresee clearly detectable levels since the expected binding energies are around 10-30 MeV, and the widths of 80-100 MeV exclude the possibility of an experimental observation. Nevertheless, a different approach of recent theoretical works by Akaishi and Yamazaki [16] shows the possibility that $\bar{K}N$ interaction, under certain conditions, could became strongly attractive allowing the formation of kaon-multinucleon systems with a binding energy varying from 86 MeV to 113 MeV, depending on the target nucleus, and with widths of 20-40 MeV. These Authors also sustain that the presence of a K^- inside the nucleus should enhance the binding energy of the system increasing the density several times that of the ordinary nuclei. Furthermore, these aggregates should be formed with higher probabilities when the kaon interact with light nuclei. These predictions looked to be confirmed by KEK E471 collaboration [17] which studying the process:

$$K^- + ^4 He \to X + N \quad (3)$$

where N is either a neutron or a proton detected by means of time of flight measurements, found two candidates in agreement with the theoretical expectations. The first one ($S^0(3115)$) was detected in the missing-mass semi-inclusive proton spectrum, while the second ($S^+(3140)$) came out in the missing-mass semi-inclusive neutron spectrum. These results have been partially withdrawn at this conference [18], nevertheless, the implications of Akaishi and Yamazaki predictions are so important that further and more detailed experimental information is necessary before closing completely the chapter. The capability of the FINUDA apparatus to detect almost all the particles emitted after K^- absorption by the nucleus is extremely useful to clarify the experimental situation. This is the reason why FINUDA is carrying out a complete set of analyzes studying the invariant-mass spectra of exclusive final states where kaon-nucleon aggregates could be formed. With the present data, some results have been already presented [19], but with the new set of targets mounted on the apparatus, the collaboration hope to draw some firm conclusion on this topic.

4.3 Neutron-rich Λ-hypernuclei

Majiling, at a previous edition of this conference [20], pointed out that Λ-hypernuclei could be better candidates than ordinary nuclei to exhibit large values of N/Z since the presence of a strange baryon give to the system extra binding (the so called Λ "glue-like" role). From the hypernuclear physics point of view, exploring systems with large N/Z can provide more information on baryon-baryon interactions, and give the possibility to study the importance of the ΛNN force related to the "coherent $\Lambda - \Sigma$ coupling" in connection with nuclear astrophysics implications [21]. In particular there is great interest on the existence of $^6_\Lambda$H since theoretical calculations including $\Lambda - \Sigma$ coupling predict a stable state with a binding energy of 5.8 MeV below the ^{5}H + Λ threshold [22]. On the other hand, without considering the $\Lambda - \Sigma$ coupling the state would be very close to the $^4_\Lambda$H + $2n$ threshold [23].

Experimentally neutron rich hypernuclei could be produced by means of reactions such as:

$$K^- + p \to \Lambda + \pi^0; \pi^0 + p \to n + \pi^+ \quad (4)$$

$$K^- + p \to \Sigma^- + \pi^+; \Sigma^- + p \leftrightarrow \Lambda + n \quad (5)$$

which have cross-sections lower than Λ-hypernuclei production via (K^-, π^-) reaction. The first experimental attempt to produce neutron-rich hypernuclei was performed at KEK using the (K^-_{stop}, π^+) reaction [24]. An upper limit for the production rate, per stopped K^-, was set for $^{12}_\Lambda$Be, $^9_\Lambda$H, $^{16}_\Lambda$C. The values are in the range of 0.6 - 2 $\times 10^{-4}$ far from the theoretical values calculated [25] which range from 10^{-6} to 10^{-7} per stopped K^-.

Recently, a KEK experiment [26] claimed to have observed $^{10}_\Lambda$Li via (π^-,K^+) reaction on a ^{10}Be target. Nevertheless, this results is not directly comparable with the theoretical predictions since no discrete levels were detected and the production cross-section has been evaluated integrating all the events in the bound region $0 < B_\Lambda < 20$ MeV. Furthermore, the above mentioned cross-section as a function of the momentum of the incoming pion display a trend opposite to the predicted one [27].

In FINUDA the search for neutron rich Λ hypernuclei has been carried out studying the reaction:

$$K^-_{stop} + ^A Z \to ^A_\Lambda (Z-2) + \pi^+ \quad (6)$$

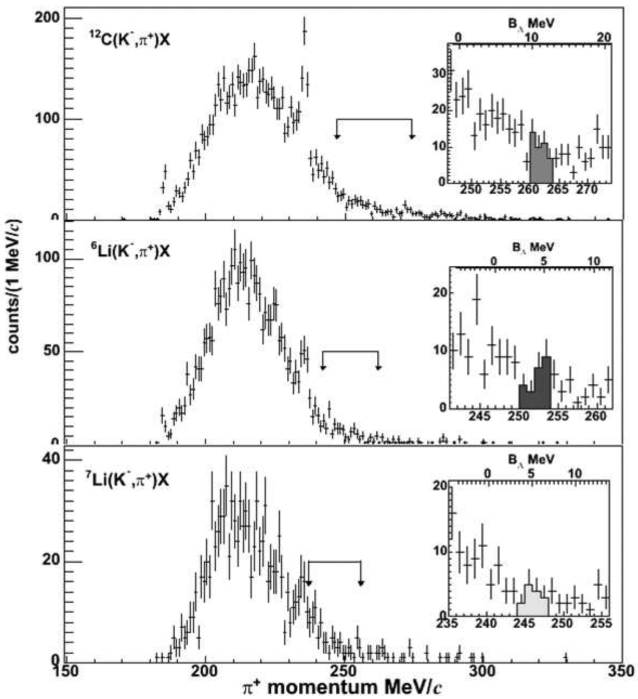

Fig. 8. Inclusive π^+ momentum spectra of ^{6}Li, ^{7}Li and ^{12}C targets. The insets show an enlarged view of of the region where neutron rich Λ hypernuclei signals are expected.

By measuring the momentum of the outgoing π^+, it is possible to determine the energy level of the hypernucleus that could be formed. For ${}^6_\Lambda$H and ${}^7_\Lambda$H the momentum of the outgoing π^+ is expected to be $\sim$ 252 and 246 MeV/c respectively.

FINUDA looked to the inclusive π^+ spectrum from ^{6}Li, ^{7}Li and ^{12}C targets (see fig. 8) which shows no evidences for the formation of Λ bound states. The upper limits for the production rates have been evaluated; the values are $(2.5 \pm 0.4_{stat}\ {}^{+0.4}_{-0.1}{}_{syst}) \times 10^{-5}$ per $K^-_{stopped}$ for ${}^6_\Lambda$H, $(4.5 \pm 0.9_{stat}\ {}^{+0.4}_{-0.1}{}_{syst}) \times 10^{-5}$ per $K^-_{stopped}$ for ${}^7_\Lambda$H, and $(2.0 \pm 0.4_{stat}\ {}^{+0.4}_{-0.1}{}_{syst}) \times 10^{-5}$ per $K^-_{stopped}$ for ${}^{12}_\Lambda$Be [28].

With the new set of targets the statistics on ${}^6_\Lambda$H and ${}^7_\Lambda$H will be increased, while new neutron-rich hypernuclear system will be studied: ${}^9_\Lambda$He, ${}^{13}_\Lambda$Be, and ${}^{16}_\Lambda$C.

5 Conclusion

The peculiar idea of FINUDA to exploit the low energy negative kaons of DAΦNE to produce hypernuclei, has proved to be winning: around 30 mullions trigger recorded with an integrated luminosity of 200 pb^{-1}, high quality results produced by all the analyzes. The detector has shown excellent versatility allowing to adapt the scientific program to follow the new trends of the sector. With the new data taking presently going on, more than 150 million's events (1fb^{-1}) will be presumably stored affording a step forward in many fields of hypernuclear physics.

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