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 analyses carried out, and describes the plans of the new data taking started in October 2006.

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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:

$$K^- + ^A Z \rightarrow ^A_\Lambda Z + \pi^- \quad (1)$$

induced by K^- from $\Phi(1020)$ decay stopping in 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^- as well as the subsequent decay products of the Λ embedded in the nucleus. Thus, hypernuclear decay mechanism can also be studied. For this purpose, a cylindrical magnetic spectrometer has been constructed, and presently data are being taken at the DAΦNE collider [1]. In the following sections the main features of the FINUDA spectrometer and the DAΦNE machine will be illustrated together with the most significant scientific results obtained so far analysing the first 200 pb^{-1} data collected from October 2003 to March 2004.

2 The DAΦNE collider

DAΦNE is an e^+e^- Φ-factory which has operated at the Frascati National Laboratory of INFN since 1998. The electron and positron beams collide at one of the two interaction points located in the two straight sections of the machine, where the experimental apparatuses can be installed. The two 510 MeV beams collide at 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 is shown in fig. 1. The Φs decay with a BR = 0.49 to K^+, K^- pairs, and these K^- are used by FINUDA to investigate reactions in several thin nuclear targets. Fig. 2 shows the measured stopping points of the negative kaons arising from Φ decay inside the FINUDA spectrometer. The Φ boost in the direction shown affects the momenta of the resultant K^+, K^-. For Φ decay at rest, the kaon momentum is 127 MeV/c, independent of direction, with an angular distribution symmetric around the beam axis. Due to the boost, the momentum of the kaons depends on the azimuthal angle of emission being slightly larger in the boost direction, and smaller on the

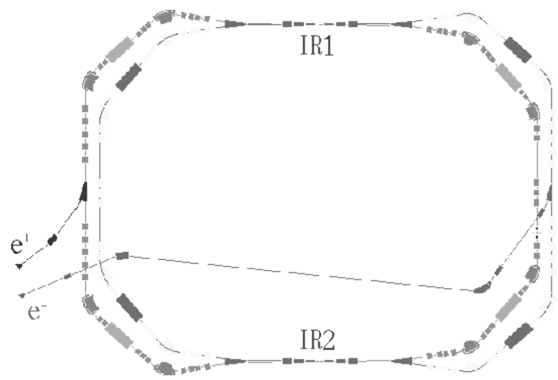

Fig. 1. Schematic layout of DAΦNE collider.

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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 number	up to 120
particle/bunch	8.9 10^{10}
max current	5.2 A

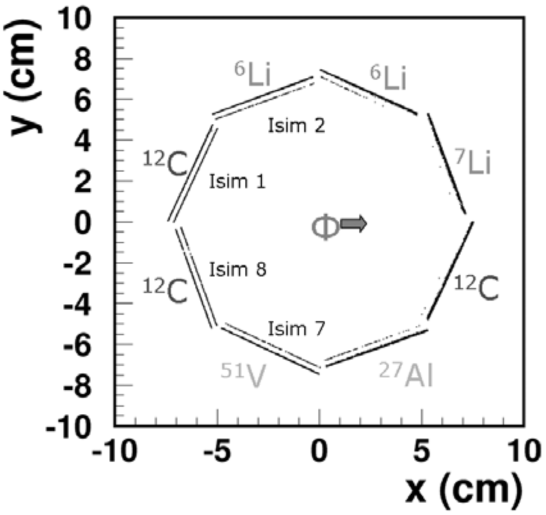

Fig. 2. Stopping points of the negative kaons from Φ decay inside the FINUDA interaction/target region. The Φ boost direction is also indicated by the central arrow. The target layout is that of the first data taking.

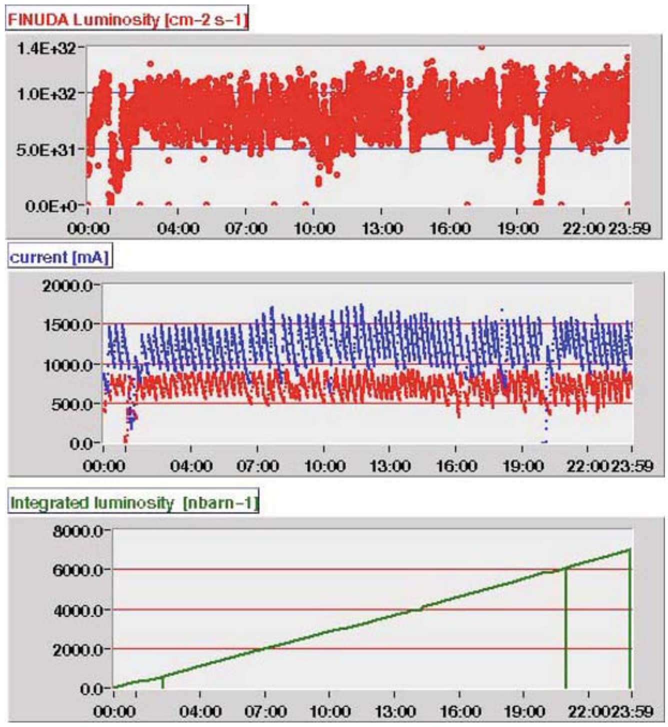

Fig. 3. DAΦNE collider average performance along 24 hours. Top: instant luminosity evaluated by FINUDA. Middle: electron and positron currents. Down: daily integrated luminosity.

opposite side. Moreover, the kaon emission distribution is no longer symmetric.

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

Presently DAΦNE is running with a top luminosity of about $1{\times}10^{32}$ cm $^{-2}$ s^{-1} delivering to the FINUDA experiment more than 5 pb $^{-1}$ per day. The machine behavior of a typical day can be seen in fig. 3.

More details on the 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) beryllium beam pipe of DAΦNE. It consists of several arrays of tracking detectors and 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 twelve 1.8 $\times$ 200 mm scintillators. The outer barrel (TOFONE) is composed of seventy two 10 $\times$ 255 cm scintillators 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 was completely re-built with new thinner scintillators. The previously used Hybrid Photo Diode devices were replaced with Hamamatsu R5505 photomultipliers, which can work with good gain and low noise in magnetic field. Furthermore, new lower-walk constant fraction discriminators have been adopted to shape the analog signals. These changes have improved the time resolution of TOFINO to 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 the 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) is used to measure the crossing point of the K^- (K^+) coming from the Φ decay, and the external array (OSIM) 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].

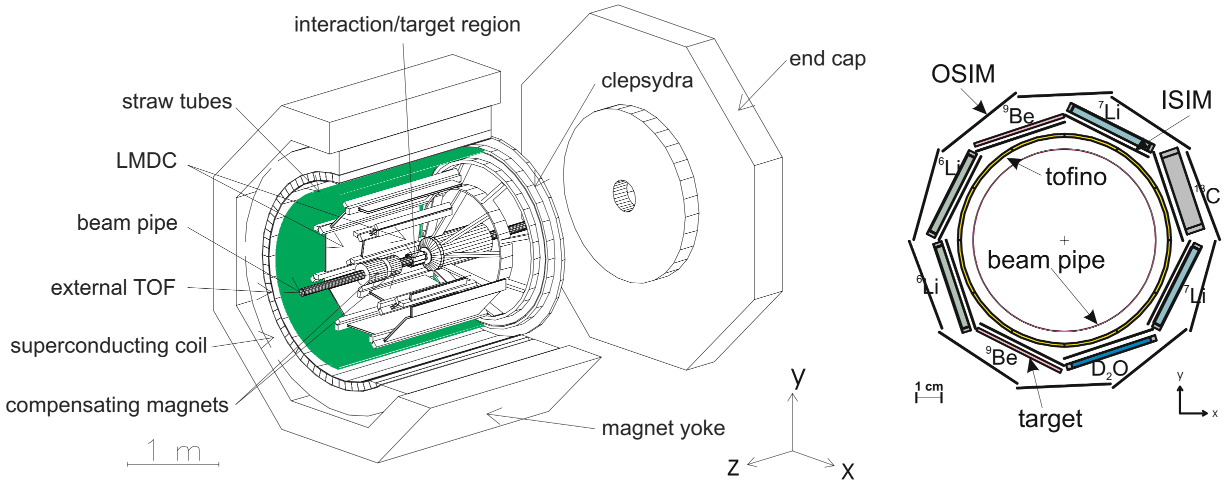

Fig. 4. Layout of the FINUDA apparatus (left). Detail of the interaction/target region (right).

The charged particle 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 to minimize the effect on momentum resolution of the multiple Coulomb scattering of low momentum particles. A sketch of the FINUDA apparatus is shown 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: the Bhabha trigger and the 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, the hypernuclear trigger asks for a multiplicity in the range 2 to 8.

At present, the FINUDA collaboration is taking data with the following targets: two ^{6}Li, two ^{7}Li, two ^{9}Be, one ^{13}C, and one 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-baryon kaon-nucleon systems;
– neutron rich hypernuclei;
– the K^+N charge exchange reaction.

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

4 The FINUDA scientific program

The FINUDA research program is extremely broad and spans the search for deeply bound kaon-nuclear states, the study of Λ-hypernuclear production, spectroscopy and decay, the existence of neutron rich hypernuclei, and the search for Σ-hypernuclei. In all these fields, FINUDA has been able to produce high quality results. Here I'll present a review of what FINUDA has already found out, pointing out where improvements could be expected with the new high statistics data set.

4.1 Hypernuclear physics

The spectroscopy of Λ-hypernuclei has been a powerful tool for studying the ΛN interaction in contrast to difficult low-statistics ΛN scattering experiments. This field received a boost with the production of high precision data coming from Ge-detector experiments measuring γ-ray transitions of hypernuclear levels resulting in measurement of ΛN spin-dependent contributions of the interaction.

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 data, good results were produced for $^{12}_{\Lambda}$C, and $^{7}_{\Lambda}$Li, hypernuclear systems. The detailed descriptions of the analyses performed, and the results obtained can be found elsewhere in these proceedings [7,8].

Figures 5 and 6 illustrate $^{12}_{\Lambda}$C and $^{7}_{\Lambda}$Li hypernuclear spectra respectively. The spectrum of $^{12}_{\Lambda}$C [9] closely resembles that measured by the 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

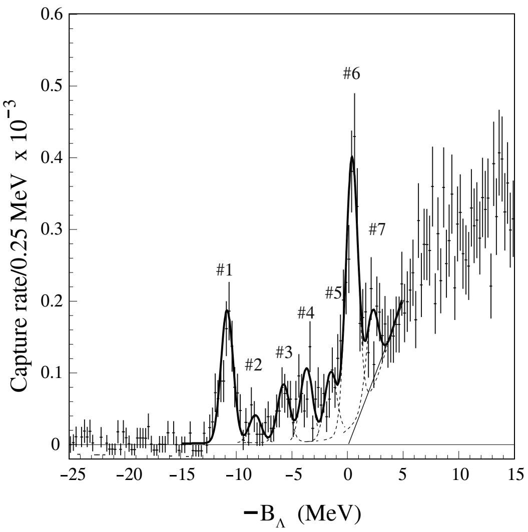

Fig. 5. ${}^{12}_{\Lambda}$C hypernuclear spectrum measured with FINUDA.

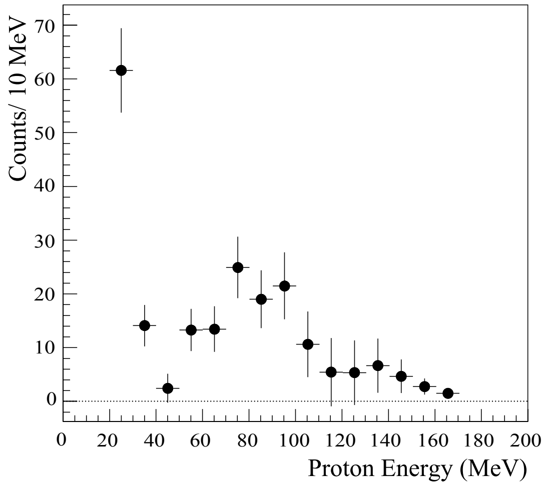

Fig. 7. Energy spectrum of the protons from non-mesonic weak-decay of ${}^{12}_{\Lambda}$C hypernucleus

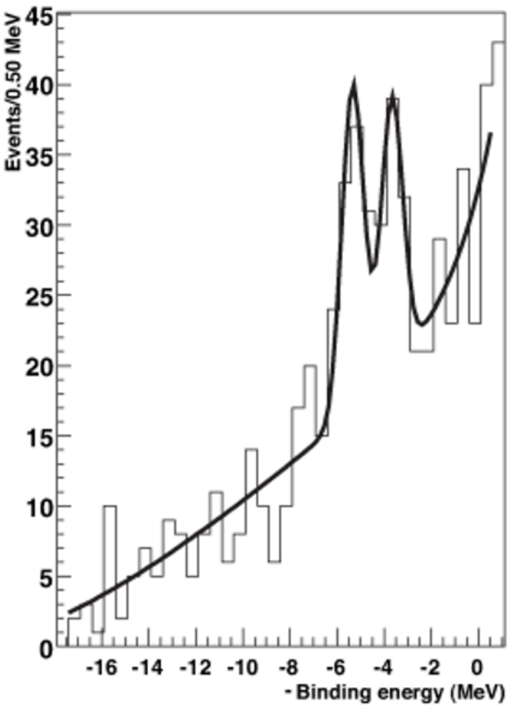

Fig. 6. ${}^{7}_{\Lambda}$Li hypernuclear spectrum measured by FINUDA.

comparable ($\sim$ 250 MeV/c for FINUDA, $\sim$ 350 MeV/c for E369). The use of carbon targets during the first data taking was essentially meant for testing the detector capabilities on a well known hypernuclear system. The quality of FINUDA data shows improvements with respect to comparable previous experiments. The energy resolution of our spectrometer is 1.1 MeV (FWHM).

Figure 6 shows our ${}^{7}_{\Lambda}$Li hypernuclear spectrum. This is one of the most studied hypernuclei in more than 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]. Considering the two levels identified by our analysis, we have tried to place them in the level scheme determined with the Hyperball. The first (left) peak could be a the ground state ($1/2^{+}$), while the second (right) peak could be the $5/2^{+}$ state.

Concerning the decay of Λ hypernuclei, the scarce statistics collected so far only permits investigation of ${}^{12}_{\Lambda}$C since three 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 work [12]. However, the comparison with a similar high statistics spectrum measured at KEK by E462/E508 experiments [13] shows some differences. The scenario will be better understood with our high statistics measurements [7].

A K^{-} impinging on a nucleus can even produce Σ hyperons, but unlike the case of a Λ particle that is stable against 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 result was theoretically explained admitting a repulsive ΣA potential at short distances [15] together with a strong isospin dependence of it, both these effects could contrast the absorptive $\Sigma N \rightarrow \Lambda N$ reaction allowing the formation of bound states. Whether Σ-bound states exist in heavier nuclei is still controversial. A recent experiment performed at KEK studied Σ-nucleus interaction with the (π^{-},K^{+}) reaction on silicon and heavier nuclear targets [16]. The results suggest a strongly repulsive Σ-nuclear potential.

In FINUDA, Σ-hypernuclear searches are performed by studying

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

The Σ hyperon then converts into a Λ via the previously mentioned strong reaction, and generally has enough momentum to escape from the nucleus and to decay in free space. The strategy for detecting such events is 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 analyses 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 for giving clear results on a topic that has became extremely relevant in the past few 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 predict 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 recent different theoretical approach by Akaishi and Yamazaki [17] shows the possibility that the $\bar{K}N$ interaction could become 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 conjecture that the presence of a K^- inside the nucleus should enhance the binding energy of the system increasing the density to several times that of the ordinary nuclei. Furthermore, these aggregates should be formed with higher probabilities when the kaon interacts with light nuclei. These predictions seemed to be confirmed by KEK E471 collaboration [18] which studied the process:

$$K^- +^4 \mathrm{He} \rightarrow X + N \quad (3)$$

where N is either a neutron or a proton detected by means of time of flight measurements, and found two candidates in agreement with the theoretical expectations. The first, $S^0(3115)$, 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 [19], nevertheless, the implications of Akaishi and Yamazaki's predictions are so important that further and more detailed experimental information is necessary before completely closing this 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. Consequently, the FINUDA collaboration is carrying out a complete set of analyses to study the invariant-mass spectra of exclusive final states where kaon-nucleon aggregates could be formed. With the present data, some results have already been presented [20], but with the new set of targets mounted on the apparatus, the collaboration hopes to draw some firm conclusions on this topic.

4.3 Neutron-rich Λ-hypernuclei

Majiling, at a previous conference in this series [21], 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 gives 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 [22]. In particular there is great interest in 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 [23]. On the other hand, without considering the $\Lambda - \Sigma$ coupling, the state would be very close to the ${}^4_\Lambda$H + $2n$ threshold [24].

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

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

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

which have cross sections lower than Λ-hypernuclear production via the (K^-, π^-) reaction. The first experimental attempt to produce neutron-rich hypernuclei was performed at KEK using the (K^-_{stop}, π^+) reaction [25]. An upper limit for the production rate, per stopped K^-, was set for ${}^{12}_\Lambda$Be, ${}^9_\Lambda$He, and ${}^{16}_\Lambda$C. The values are in the range of 0.6 - 2 $\times$ 10^{-4}, far from the calculated theoretical values [26] which range from 10^{-6} to 10^{-7} per stopped K^-.

Recently, a KEK experiment [27] claimed to have observed ${}^{10}_\Lambda$Li via (π^-, K^+) reaction on a ^{10}B target. Nevertheless, this result is not directly comparable with the theoretical predictions since no discrete level was detected and the production cross section has been evaluated by 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 displays a trend opposite to predictions [28].

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

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

By measuring the momentum of the outgoing π^+, it is possible to determine the energy level of the hypernucleus that is 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.

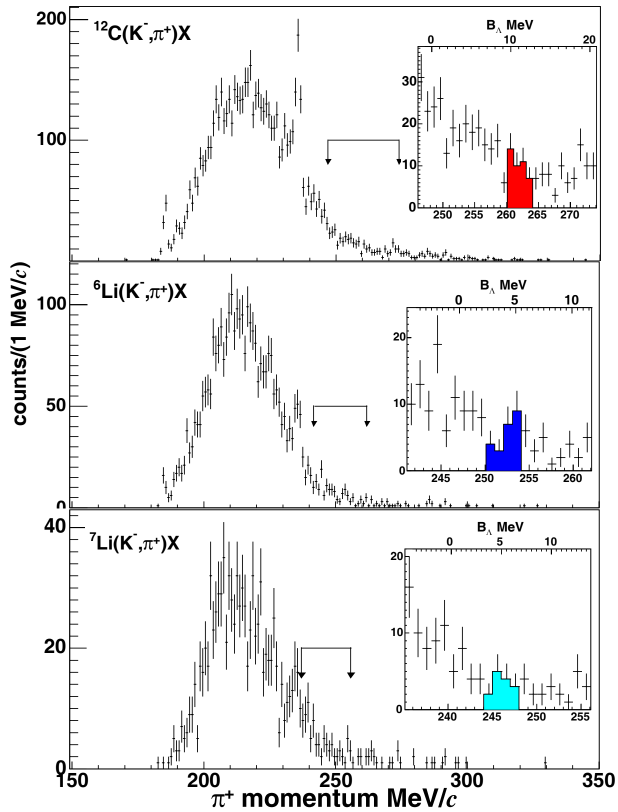

Fig. 8. Inclusive π^+ momentum spectra of ^{6}Li, ^{7}Li and ^{12}C targets. The insets show an enlarged view of of the region where signals of neutron rich Λ hypernuclei signals are expected.

With FINUDA, we looked into the inclusive π^+ spectra from ^{6}Li, ^{7}Li and ^{12}C targets (see fig. 8) which show no evidences for the formation of Λ bound states. The upper limits (90% C.L.) evaluated for the production rates 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 [29].

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

5 Conclusion

The unique idea that FINUDA can exploit the low energy negative kaons of DAΦNE to produce hypernuclei has proved to be a winner: around 30 millions triggers were recorded with an integrated luminosity of 200 pb^{-1} and high quality results were produced by all the analyses. The detector has shown excellent versatility allowing us 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 events (1fb^{-1}) will presumably be stored affording a step forward in many fields of hypernuclear physics.

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