FIRST RESULTS ON HYPERNUCLEAR PHYSICS FROM FINUDA AT DAΦNE

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FINUDA experiment on hypernuclear physics has completed the first round of data taking at the DAΦNE ϕ-factory. Here hypernuclei are produced by the strangeness exchange reaction induced by stopped K^-, coming from the $\phi(1020)$ decay on nuclear targets. Studies on hypernuclear spectroscopy and decay can be performed simultaneously using the same apparatus. Preliminary results on hypernuclear spectroscopy on $^{12}_{\Lambda}C$, rare decays of $^{4}_{\Lambda}He$, search for neutron-rich hypernuclei, Σ-hypernuclei and deeply bound kaonic states are reported here.

1. Introduction

Since 1953, when the first hyperfragment was observed through its decay by Danysz and Pniewski[1], the research on hypernuclear physics has known different phases of development and many experiments have been designed and performed to answer to new arising questions. However the major progress has been done in the last 20 years, when this field has been extensively studied both experimentally and theoretically, especially at KEK and BNL, where suitable K^- and π^+ beams were available, allowing to increase the production rate of Λ-hypernuclei.

Hypernuclear physics add a new dimension (strangeness different than zero) to the world of nuclei, therefore investigation of Λ-hypernuclei can be considered as the first step in the study of flavoured nuclei, which opens the road to a rich field of research. Up to now a lot of data have been produced especially on Λ-hypernuclei and the existence of Σ-hypernuclei is still debated. Next challenge for the future experiments under design at J-PARC and at GSI will be the study of the double-Λ-hypernuclei.

1.1. *FINUDA Experiment*

FINUDA[2,3] can be considered a new generation experiment on hypernuclear physics, because for the first time hypernuclear spectroscopy and decay can be studied simultaneously with high statistics exploiting a very large solid angle, typical of collider apparata. Indeed the experiment is installed at the DAΦNE[4] ϕ-factory in Frascati which at present can deliver about 10 millions of ϕ/day. The ϕ's, produced in the collisions of e^+ and e^-, circulating in opposite directions at an energy of 510 MeV each, decays at rest mostly into K^+K^- (49%) and $K^0_S K^0_L$ (34%). Thus DAΦNE can be considered as a source of monochromatic, collinear and tagged pairs of neutral and charged kaons. The clever idea[5] to perform a fixed target experiment, such as FINUDA, at a collider was the possibility to stop the K^- from the ϕ decay in thin nuclear targets ($0.1\div0.3$ gcm^{-2}), due to its low energy ($\sim$ 16 MeV), in order to produce Λ-hypernuclei through the reaction:

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

Therefore K^-'s can be stopped with minimal straggling very close to the target surface, allowing to achieve unprecedented resolution on the measurement of the outgoing π^- momentum, which is directly related to the energy levels of the produced hypernucleus.

The π^-'s momenta are measured by a high resolution magnetic spectrometer, optimized for momenta ranging between 250÷280 MeV/c, with an energy resolution better than 1 MeV. Since the best resolution obtained up to now in hypernuclear spectroscopy by KEK-E369[6] is 1.45 keV , a resolution better than 1 MeV is in competition only with the experiments at Jefferson Laboratory[7].

Λ-hypernucleus spectroscopy with high resolution, extended over the full nuclear mass range, constitutes a top priority of the physics program. In particular a step forward is expected in the medium-high mass region, because the existent data are still scarce and FINUDA can use any kind of nuclear target, as long as machinable in thin foils.

For all the nuclei but the lightest ones, when the Λ is embedded in the nuclear medium, the mesonic decay modes are strongly suppressed due to a reduction of the phase space combined with the Pauli blocking of the recoil nucleon ($p_N \sim 100$ MeV/c). So the non-mesonic modes:

$${}^{A}_{\Lambda}Z \; \rightarrow \; {}^{(A-2)}(Z-1) \; + \; n \; + \; p, \qquad {}^{A}_{\Lambda}Z \; \rightarrow \; {}^{(A-2)}Z \; + \; n \; + \; n \tag{2}$$

are dominant[8], since phase space is wider and the nucleons in the final state are not affected by Pauli blocking ($p_N \sim 417$ MeV/c).

A comprehensive study of the partial decay widths Γ_p and Γ_n, of the p-induced and n-induced processes (2) and mean lifetime of the hypernucleus is important to study the validity of the well-known $\Delta I = 1/2$ rule, which gives information on the structure of the weak Hamiltonian.

1.2. *The Apparatus*

A detailed description of the FINUDA detectors can be found elsewhere[2,9], only general features are given here. The apparatus is a magnetic spectrometer with cylindrical geometry covering a large solid angle $> 2\pi$ sr. In the spectrometer three main parts can be distinguished: an inner section surrounding the interaction region (beam pipe, thin scintillator counter barrel, 8-fold nuclear target, Si-microstrip detectors); an external tracker (low-mass drift chambers 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 m^3) is immersed in a He atmosphere to minimize multiple Coulomb scattering. The geometry of the spectrometer, the position of the detetctors and the value of the magnetic field have been optimized for maximizing the momentum resolution and acceptance for the prompt π^- from hypernucleus formation Eq.(1). Design momentum resolution is Δp/p = 3.5×10^{-3} (FWHM), corresponding to a resolution of 830 keV in the hypernuclear energy levels. Concerning the trigger, a description of performances is given elsewhere[10], here we just point out that the rejection power for the main background coming from the machine, the Touschek effect (intra-beam scattering in the same bunch), is of the order of 10^6.

2. Physics Program and Features of the First Data Taking

One of the main features of FINUDA experiment is that it allows to study simultaneously hypernuclear spectroscopy and hypernuclear decays. For the first data taking period the following targets have been chosen:

- *Light targets*: two of ^6Li and one of ^7Li. Since the $^6_\Lambda Li$ hypernucleus is unstable for nucleon emission, it decays into hyperfragments such as $^5_\Lambda He+p$, $^4_\Lambda He+p+n$ and $^4_\Lambda H+p+p$. $^5_\Lambda He$ can be identified by selecting the end-part of the momentum spectrum of the π^- from reaction in Eq.(1). $^4_\Lambda He$ can be recognized by its rare decay channels: $^4_\Lambda He \rightarrow d+d$ and $^4_\Lambda He \rightarrow p+^3H$ never observed before. $^6_\Lambda Li$ target is also used for searching neutron-rich hypernuclei[11]. The low-lying excited states of $^7_\Lambda Li$ hypernucleus has been extensively studied at KEK with high resolution($\sim$ 3 keV) γ-spectroscopy[12], but its weak decay observables were never studied.
- *Three targets of* ^{12}C. The most deeply studied p-shell hypernucleus is $^{12}_\Lambda C$, the existing measurements at KEK[6] can be taken as a reference by FINUDA. Moreover, statistical accuracy and energy resolution can be improved.
- *Medium-heavy targets*: ^{27}Al and ^{51}V. Existing data on $^{27}_\Lambda Al$ produced with K^- in flight[13] are poor of statistics and the energy resolution is very low (6 MeV FWHM). Therefore it is very interesting to look at the excitation spectrum with higher resolution and to measure its ground state capture rate. The excitation spectrum of $^{51}_\Lambda V$ was measured at KEK[14] with an energy resolution of

1.65 MeV. Peaks corresponding to the p and d single-particle orbits show a splitting, which has been attributed to a not negligible Λ spin-orbit potential. The ultimate energy resolution of FINUDA would shed light on this issue.

The first FINUDA data taking run started in the beginning of December 2003 up to the end of March 2004. A total integrated luminosity (L_{int}) of 250 pb^{-1} was delivered to the experiment. Taking into account the time for machine tuning and detector debugging, 190 pb^{-1} are useful for data analysis. The maximum daily L_{int} was 4 pb^{-1} and the top luminosity was 6×10^{31}cm$^{-2}s^{-1}$. At a luminosity of 5×10^{31}cm$^{-2}s^{-1}$ FINUDA can provide a high hypernuclear formation rate: 40 hypernuclei/hour with 10^{-3} capture rates. The luminosity was continuously monitored detecting the Bhabha events, $e^+e^- \rightarrow e^+e^-$, by means of a dedicated trigger. The two-body decays of kaons, $K^+ \rightarrow \mu^+\nu_\mu$ and $K^+ \rightarrow \pi^+\pi^o$, were also recorded, since these events allow to check the stability of the momentum resolution of the spectrometer.

3. Preliminary Results on Spectroscopy

The whole sample of $\sim 3\times10^7$ collected events has been processed selecting hypernuclear events with some cuts chosen in order to optimize the signal to noise ratio (see Refs. 15, 16 for details). Figure 1 shows the momentum distribution for the selected π^- in the eight targets, clean hypernuclear structures appear in the expected momentum range.

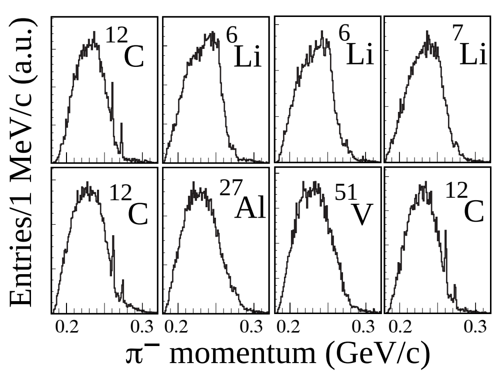

Figure 1. *Momentum spectra of the selected forward pions on the eight targets.*

As first step only one ^{12}C target has been analyzed, therefore about 20% of the available statistics has been used. Some simulations have been done in order to get a parametrization of the background spectrum which has been subtracted from the measured spectrum. The result is shown in Fig. 2(a): two prominent peaks at $B_\Lambda \simeq 11$ MeV and 0 MeV correspond to the ground state (s_Λ) and to the excited state of the $^{12}_{\Lambda}C$ with the Λ in the p-shell (p_Λ). The FINUDA preliminary result on $^{12}_{\Lambda}C$ is compared with the result of experiment KEK-E369[6] (Fig. 2(b)), which produced hypernuclei via (π^+, K^+) reaction: peaks #1 , #3 and #4 in Fig. 2(a) are consistent with peaks #1, #5, #6 in Fig. 2(b), while peak #2 does not appear in E369 data. We have set the energy resolution at $\sigma_E = 600$ keV ($\Delta E = 1.45$ MeV, $\Delta p/p = 0.6\%$), given by the peak at $B_\Lambda = 0$.

The very preliminary capture rates for $^{12}_{\Lambda}C$ formation have been estimated to be $\sim\ 1.8\times\ 10^{-3}/K^-_{stop}$ for the ground state and $3.3\times\ 10^{-3}/K^-_{stop}$ for the p_Λ state. The structure in the region between the two peaks needs to be studied with the full statistics on ^{12}C.

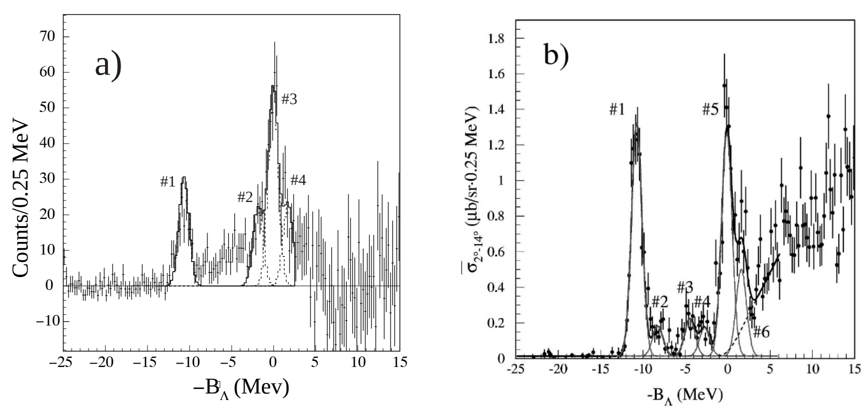

Figure 2. *^{12}C hypernuclear mass spectrua. a) FINUDA spectrum after background subtraction and for comparison b) E369 spectrum at KEK.*

4. Preliminary Results on Rare Decays, Neutron-Rich Hypernuclei, Σ bound States and Kaonic Nuclei

Exploiting the large solid angle and the excellent tracking capabilities of the apparatus for the products coming from hypernucleus formation and decay, different physics topics have been investigated.

By means of the ^{6}Li target the rare non mesonic decay ${}^{4}_{\Lambda}He \rightarrow d + d$, never observed before[17], is under study. At present 9 candidate events with the expected topology have been found[18], Fig. 3 shows a typical event.

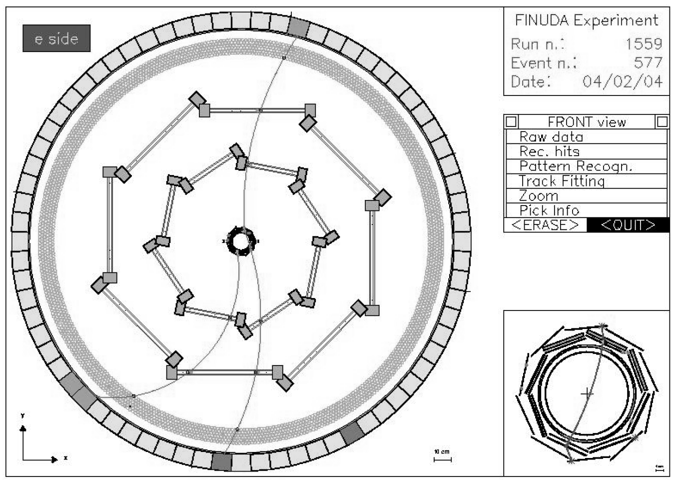

Figure 3. *Rare non mesonic decay* ${}^{4}_{\Lambda}He \rightarrow d + d$

The existence of Λ-hypernuclei with a large neutron excess has been theoretically predicted[11] but not observed up to now, apart from a recently announced measurement with ^{10}B target with KEK-E521[19] experiment. Formation of such hypernuclei should be possible because of the "extra-binding" energy provided by the Λ hyperon. Search for neutron-rich hypernuclei has been done[20] in FINUDA looking at the reaction $K^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}(Z-2) + \pi^+$ using ^{12}C, ^{6}Li and ^{7}Li targets. The reaction should proceed through two elementary mechanisms, therefore expected production rates are very low, in the range $10^{-6} \div 10^{-5}/K^-_{stop}$. The momentum distributions for the π^+ from the formation of neutron-rich hypernuclei are shown in Fig. 4. Since no evidence of peaks have been found, only upper limits at 90% $C.L.$ are given: 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 value for ${}^{12}_{\Lambda}Be$ improves previous KEK result[21], but values for ${}^{6}_{\Lambda}H$ and ${}^{7}_{\Lambda}H$ have been estimated for the first time.

Concerning the Σ-hypernuclei only the bound state in ${}^{4}_{\Sigma}He$, produced by in flight (K^-, π^-) reaction, has been established[22] in the past, but it is considered an exception due to the effect of a strongly isospin-dependent Σ-nucleus potential. Preliminary analysis[23] has been done on the ^{12}C target data sample to identify the reaction $K^-_{stop} + ^{12}C \rightarrow\ ^{12}_{\Sigma^-}Be + \pi^+$ and the following decays $^{12}_{\Sigma^-}Be \rightarrow\ ^{10}_{\Sigma^-}Be + \Lambda + n$ and $\Lambda \rightarrow \pi^- + p$. The inclusive yield of the momentum distribution of π^+ from hypernucleus formation drastically reduces when coincidences with the π^- and the p from Λ decay are required. Only some events remain in the range of 150÷200 MeV/c. Moreover the topology of the events can be examined in details to check whether the Λ decay secondary vertex is present, indeed such a feature is a unique signature of a Σ-hypernucleus, which can be verified only in an apparatus such as FINUDA.

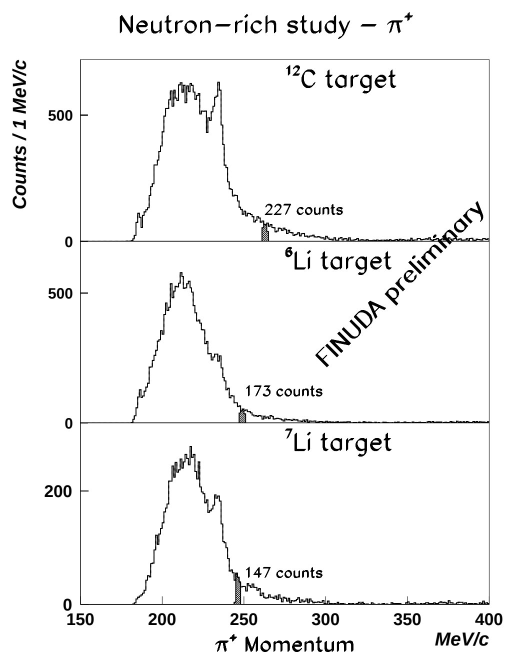

Figure 4. *Momentum spectra of π^+ from the formation of neutron-rich hypernuclei.*

Search for deeply-bound kaonic states[24] is under way in FINUDA, actually the spectrometer allows once more to detect a Λ hyperon emitted from the decay of kaonic nuclei, through its decay mode into p and π^-. The use of tagging together with the analysis of the invariant mass of the Λ-p system can contribute to identify the formation of such states with strangeness. Preliminary results strongly suggest the existence of K^-pp, the lightest kaon bound system.

5. Conclusions

FINUDA has successfully collected 3×10^7 events on tape at the DAΦNE ϕ-factory. Preliminary results on hypernuclear spectroscopy of ${}^{12}_{\Lambda}C$ show a quality comparable to the best world data set. Several hypernuclear physics topics have been investigated and preliminary results on neutron-rich hypernuclei, Σ-hypernuclei and deeply bound kaonic states look very promising for further analysis and future data taking. These results should improve significantly with progress in data analysis.

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