The FINUDA experiment: a new powerful laboratory for studies of strangeness in nuclear matter

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Abstract.
FINUDA is the very first fixed-target experiment carried on at a collider. The detector provides the reconstruction of complex multi-particles events with very high performances, allowing to cover a large physics program, including very relevant items concerning nuclear matter with strangeness $\neq 0$. The analysis developed after the first FINUDA data taking has given some interesting hints, stimulating deeper investigations. The most relevant results are shown and discussed.

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INTRODUCTION

The FINUDA (acronym for "Fisica NUcleare a DAΦNE") experiment, carried on at the Φ-factory DAΦNE, Laboratori Nazionali di Frascati of the Istituto Nazionale di Fisica Nucleare (Italy), is an unconventional example of (hyper)nuclear physics experiment, in which a fixed target array is employed within a collider. DAΦNE (Double Annular Φ-factory for Nice Experiments) produces the $\phi(1020)$ meson through the $e^+ + e^- \longrightarrow \phi$ collision at a center-of-mass energy $\sqrt{s} = 1020$ MeV. The main idea of the experiment is to use the low kinetic energy ($\simeq 16$ MeV) K^-'s emitted in the $\phi \longrightarrow K^+ + K^-$ decay (B.R. = 49%) as a beam, and to stop them in very thin targets ($0.2 \div 0.4$ g cm^{-2}), producing Λ hypernuclei through the strangeness-exchange reactions $K^-_{\mathrm{stop}} + {}^AZ \longrightarrow {}^A_\Lambda Z + \pi^-$ (${}^AZ$ indicates the target nucleus and ${}^A_\Lambda Z$ the Λ hypernucleus, containing Z protons, $A-Z-1$ neutrons and a Λ hyperon). The hyperon binding energy in the hypernucleus is measured through the π^- momentum. The use of K^-'s from the ϕ decay as a beam provides unique advantages with respect to the extracted beams from hadron machines, as explained in ref. [1].

The FINUDA detector, described in ref. [2], is designed as a typical collider experiment, and provides a full event multi-tracking reconstruction with a high momentum resolution for charged particles and a large geometrical acceptance; so it allows a simultaneous analysis of the formation and the decay processes for strange hadronic systems. Hence, the study of a wide-ranging physics program is possible, from the aspects related to the hyperon-nucleon strong and weak interaction at low energies, to the features of strange nuclear matter systems.

The first FINUDA data taking started in November 2003 and ended in March 2004, with an average DAΦNE luminosity of $\mathscr{L} \sim 0.4 \cdot 10^{32}$ cm^{-2}s^{-1} and a total integrated luminosity of ~ 190 pb^{-1}. The most interesting results will be shown here.

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[*]This paper is dedicated to the memory of our colleague and friend Valerio Filippini

HYPERNUCLEAR SPECTROSCOPY

FINUDA has measured the ${}^{12}_{\Lambda}$C hypernucleus excitation spectrum, shown in fig. 1 a), with an energy resolution of 1.29 MeV FWHM; this improves the result obtained in 2001 by the E369 experiment at KEK, in which the same spectrum was measured, with an energy resolution of 1.45 MeV FWHM, by means of (π^+, K$^+$) reaction with a 1.05 GeV/c beam [3]. Apart from some differences in the peak yields, related to the different production reactions, the spectra from the two experiments are similar, as far as energy levels localization is concerned, and a nice agreement on the energy levels is found, within the experimental uncertainties (see ref. [4] for a deep discussion).

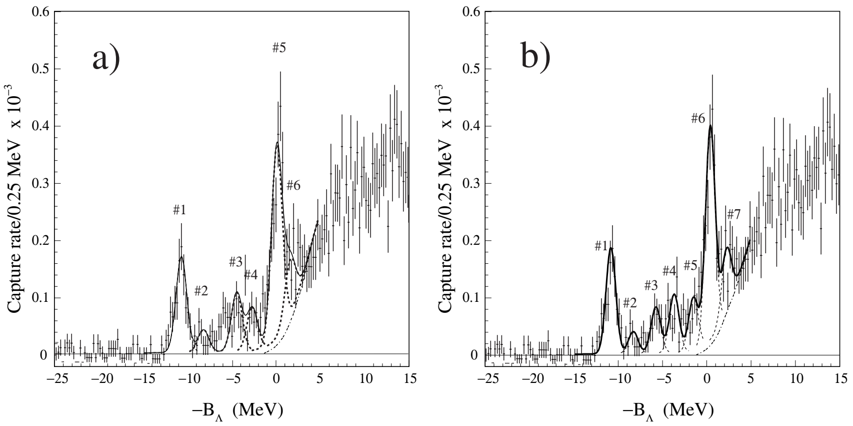

FIGURE 1. ${}^{12}_{\Lambda}$C excitation spectrum from FINUDA data: a) fitted with 6 gaussian peaks; b) fitted with 7 gaussian peaks.

It is worth mentioning that the excitation spectrum may be fitted, with a better reduced χ^2 value, by adding a further gaussian contribution (corresponding to a hypernuclear energy level with B$_\Lambda$ = 1.6 MeV) to the six already observed levels; this structure (labelled with #5 in fig. 1 b), could be interpreted as a new observed ${}^{12}_{\Lambda}$C state: the positive-parity excited states of the ^{11}C core lying in the same energy region could contribute to it, as suggested in ref. [5].

SEARCH FOR NEUTRON-RICH HYPERNUCLEI

The existence of neutron-rich Λ hypernuclei with a large neutron excess (N/Z ratio more than double the typical values for ordinary nuclei) has been theoretically predicted [6] but never observed up to now. A search for such hypernuclei is an intriguing challenge, in the attempt to expand our knowledge on nuclear systems towards the limits of stability in the $S = -1$ plane and to study their structure at high N/Z ratio; finally, a very relevant feedback with astrophysics exists, mostly in the study of very high-density matter in neutron stars [7].

FINUDA is an ideal laboratory to investigate the existence of hypernuclei with high N/Z ratios, which can be produced in two-step elementary reaction mechanisms, leading to the global nuclear reactions $\mathrm{K}^-_{\mathrm{stop}} + {}^{A}Z \longrightarrow {}^{A}_{\Lambda}(Z-2) + \pi^+$.

On the target nuclei ^{6}Li and ^{7}Li and ^{12}C, employed during the first FINUDA data taking, the above reactions are expected to produce the neutron-rich Λ hypernuclei ${}^{6}_{\Lambda}$H, ${}^{7}_{\Lambda}$H and ${}^{12}_{\Lambda}$Be, plus a π^+, characterizing their signature. From the available data, an upper limit for the production rates of these neutron-rich hypernuclei with the ($\mathrm{K}^-_{\mathrm{stop}}$, π^+) reaction has been evaluated, within a 90% confidence level. The event selection required a successfully reconstructed π^+, associated to the K$^-$ stopping point in the target and having a momentum corresponding to the Λ bound region, as explained in ref. [8]. The preliminary results are summarized in the table 1.

TABLE 1. Evaluated upper limits (at 90% C.L.) for the neutron-rich hypernuclei ${}^{12}_{\Lambda}$Be, ${}^{6}_{\Lambda}$H and ${}^{7}_{\Lambda}$H production rates.

Target	Hypernucleus	Upper Limit
^{6}Li	${}^{6}_{\Lambda}$H	[3.4 $\pm$ 0.2 (stat)] $\cdot$ 10^{-5} / $\mathrm{K}^-_{\mathrm{stop}}$
^{7}Li	${}^{7}_{\Lambda}$H	[4.6 $\pm$ 0.4 (stat)] $\cdot$ 10^{-5} / $\mathrm{K}^-_{\mathrm{stop}}$
^{12}C	${}^{12}_{\Lambda}$Be	[4.6 $\pm$ 0.2 (stat)] $\cdot$ 10^{-5} / $\mathrm{K}^-_{\mathrm{stop}}$

Since the available experimental data on these neutron-rich hypernuclei are extremely poor at present, these hints represent a significant step forward and encourage further efforts to verify their existence. It has to be stressed that the limits reported here are the very first experimental data extracted for ${}^{6}_{\Lambda}$H and ${}^{7}_{\Lambda}$H, while for ${}^{12}_{\Lambda}$Be the new upper limit lowers the previous one measured at KEK in 1996 [9].

SEARCH FOR $\overline{\mathrm{K}}$-BOUND NUCLEAR STATES

Possible signatures of deeply bound kaonic nuclear states have been recently reported [10, 11, 12], in agreement with the predictions of the theoretical works [13, 14], that foresee a strongly attractive potential for the $I = 0$ $\overline{\mathrm{K}}$N interaction and suggest the existence of deeply bound nuclear $\overline{\mathrm{K}}$ states in light nuclei with binding energies of $\sim 50 \div 100$ MeV.

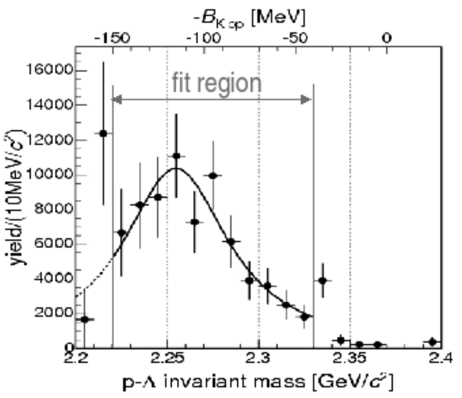

FIGURE 2. Invariant mass of a Λ and a proton in back-to-back correlation from light targets, as reconstructed in FINUDA.

On the other hand, plenty of theoretical evaluations exist that predict much shallower trends for the K^--nucleus potential depth and substantially exclude the possibility of observing such states [15, 16, 17, 18]. Thus, it is urgent to verify experimentally whether the observed signals really indicate a kaon-bound state production or not.

FINUDA is able to detect the Λ hyperon through its p + π^- decay mode and thus to identify the formation of strange bound states from their decays into $\Lambda + X$. In particular, the existence of the light K^-pp deeply bound state has been investigated, by means of the detection of its decay into Λ + p; the event selection was based on the back-to-back Λ-p pair reconstruction, as explained in ref. [19].

The invariant mass distribution obtained for the Λ-p pairs is shown in fig. 2 for the ^{6}Li, ^{7}Li and ^{12}C targets. A significant mass decrease of the K^-pp system with respect to the sum of a kaon and two proton masses ($M_{\mathrm{K}} + 2\,M_{\mathrm{p}} = 2.370$ GeV/c^2) is clearly observed: it can be interpreted as due to the existence of a deeply bound state, with a binding energy B = 115 $^{+6}_{-5}$ (stat) $^{+3}_{-4}$ (syst) MeV and a width Γ = 67 $^{+14}_{-11}$ (stat) $^{+2}_{-3}$ (syst). The yield of the $\mathrm{K}^-\mathrm{pp} \to \Lambda + \mathrm{p}$ process has been estimated to be of the order of 10^{-3} / $\mathrm{K}^-_{\mathrm{stop}}$ [19]. The simple two-nucleon absorption does not seem to provide a good explanation of the spectrum.

FUTURE PLANS

The next FINUDA data taking is going to start at the mid-2006, and the collection of ~ 1 fb^{-1} is foreseen, at an upgraded luminosity of $\sim 10^{32}$ cm^{-2}s^{-1}. This statistics increase will improve the significance of our previous data, and hopefully will discover new aspects of strange nuclear systems.

After 2006, a further machine luminosity upgrade should reach a value $\sim 10^{33}$ cm^{-2}s^{-1}. In this respect, a development of the FINUDA detector itself has been proposed [20], in order to study the spin-dependent level fine splittings for different hypernuclei.

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