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FINUDA results on $^{7}_{\Lambda}Li$

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Abstract. The FINUDA experiment produces Λ-hypernuclei stopping in thin targets the K^-s coming from the decay of the Φ (1020) meson inside the DAΦNE $e^+ - e^-$ collider machine at INFN Laboratori Nazionali di Frascati. In this paper we report the results concerning the production of $^{7}_{\Lambda}$Li. The absolute production rate and the best up-to-date hypernuclear spectrum obtained in formation experiments, with an energy resolution of 1.1 MeV (FWHM), are unveiled.

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1 Introduction

FINUDA is a hypernuclear physics experiment, the first to take place at a collider, that utilizes the DAΦNE Φ factory machine of the INFN "Laboratori Nazionali di Frascati" in the neighborhood of Rome. DAΦNE consists of two accelerating rings in which positron and electron ($e^+ - e^-$) beams can circulate and collide. The energy of each beam is 510 MeV in order to produce the Φ(1020) meson in the collisions. The specific aim of FINUDA is to produce hypernuclei by stopping the negative kaons originating from the Φ decay. Indeed this particle emits, with a branching ratio of 49.2%, two back-to-back kaons ($\Phi \to K^+K^-$) with a very low kinetic energy of $\simeq 16$ MeV. In this way an unconventional K^- beam of very low energy is available for the experiment. The main idea of FINUDA is to slow down to rest the negative kaons in thin solid targets (0.1-0.2 g/cm^2 compared to some g/cm^2 of previous hypernuclear fixed-target experiments) allowing for the production of Λ hypernuclei through the strangeness-exchange reaction $K^-_{stop} + ^A Z \to ^A_\Lambda Z + \pi^-$. $^A Z$ indicates the target nucleus

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and ${}^{A}_{\Lambda}Z$ the Λ hypernucleus in which a Λ particle replaced a neutron. By precisely measuring the momentum of the outgoing π^-, it is possible to determine the energy level of the produced hypernucleus.

Since the discovery of the first hypernucleus [1], late in 1953, many hypernuclei have been studied with great effort. Along with ${}^{12}_{\Lambda}C$, about which FINUDA recently reported his results [2], ${}^{7}_{\Lambda}$Li is one of the most studied. In this paper we present the first FINUDA results related to this hypernucleus.

The best, up to now, ${}^{7}_{\Lambda}$Li hypernuclear spectrum in formation experiments has been obtained by the E336 experiment at KEK [3,4], using the (π^+, K$^+$) production process, with an energy resolution of 2.2 MeV (FWHM). Recently, the experiments E419 at KEK and E930 at BNL took advantage of a large acceptance germanium detector array (Hyperball) to perform high resolution γ-spectroscopy of ${}^{7}_{\Lambda}$Li, clarifying the level scheme and the energies of the bound states as shown in Fig. 1 ([5–7] and references therein). The excitation energies of Fig. 1 are referred to the binding energy B$_\Lambda$ of the ${}^{7}_{\Lambda}$Li ground state (5.58 ± 0.03 MeV) measured by few emulsion experiments in the 60's and 70's ([8] and references therein).

In this paper the ${}^{7}_{\Lambda}$Li hypernuclear spectrum with an energy resolution of 1.1 MeV (FWHM) obtained by the FINUDA experiment with the process $K^-_{stop} +^A Z \rightarrow^A_\Lambda Z + \pi^-$ is presented along with discussion about energy level populations and absolute rate production.

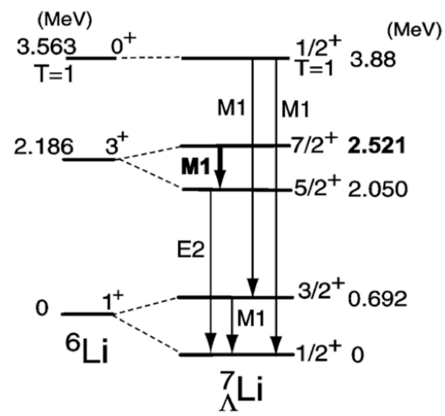

Fig. 1. Level scheme of ${}^{7}_{\Lambda}$Li from Hyperball experiments [5,7]

2 The FINUDA experiment

FINUDA presents an unconventional apparatus for hypernuclear physics studies having a set-up typical of collider experiments designed for obtaining a large acceptance around the beam interaction region. The whole apparatus is contained inside the magnet yoke of a superconducting solenoid which provides a homogeneous magnetic field of 1.0 T over a cylindrical volume of 146 cm in radius and 211 cm in length: a schematic view of the apparatus is shown in Fig. 1 of [2]. The particles coming from the e^+-e^- interaction points travel radially outwards encountering three main apparatus regions (called respectively *target*, *tracking* and *time of flight*). In the first one, the *target region*, schematically shown in Fig. 2 of [2], a barrel of 12 thin scintillators (2.4 cm thick), called TOFINO, surrounds the beam pipe and detects the back-to-back kaons coming from the Φ decay. The signals from these detectors are used for triggering purposes. The scintillators are surrounded by an octagonal array of silicon microstrip detectors, called ISIM and having a spatial resolution of about 30 μm and a good energy resolution (ΔE/Δx of 20% for the low energy kaons from the Φ decay). They trace the kaons before entering the 8 target modules that face the silicon detectors at a distance of a couple of millimeters. For the starting run the following targets were selected: two ^{6}Li, one ^{7}Li, three ^{12}C, one ^{27}Al and one ^{51}V. The interaction point of the kaons inside the target is determined with a precision of about 800 μm, limited by the angular straggling in the last part of the path before stop. The products of the interaction of the kaons inside the targets are then traced in the *tracking region.* First they are detected by another array of ten silicon microstrip detectors (OSIM) placed close to the targets (see Fig. 2 of [2]). They are also used for mass discrimination purposes having a good energy resolution. Moving radially outwards two arrays of eight planar low-mass drift chambers (LMDC) provide the measurement of the particle trajectories with a spatial resolution of $\sigma_{\rho\Phi} \sim 150$ μm and $\sigma_z \sim 1$ cm. A third type of detector at 1.1 m from the center completes the tracking system: six layers of longitudinal and stereo straw tubes with a spatial resolution of $\sigma_{\rho\Phi} \sim 150$ μm and $\sigma_z \sim 500$ μm. A third, *time of flight*, region finalize the FINUDA experimental apparatus. It is composed by a barrel of 72 scintillator slabs (10 cm wide and 255 cm long) that provide signals for the first level trigger, for the time-of-flight measurement of the charged particles and for the detection of neutrons. Details about the FINUDA experimental spectrometer can be found in [2] and references therein.

FINUDA collected the first data during the december 2003 - march 2004 data taking period with a daily integrated luminosity of about 4 pb^{-1}, corresponding to a total of about 200 pb^{-1}. Events with two signals above kaon threshold in two back-to-back TOFINO slabs and a fast coincidence with a TOFONE barrel signal were triggered and recorded to disk being good candidates of hypernuclear formation. Details about the event reconstruction procedure can be found in [2].

3 Data analysis

Hypernuclear candidate events are selected by requiring the simultaneous presence of a K$^-$ stopped inside the ^{7}Li target and of a π^- originating from the same target and traveling through the whole apparatus reaching the external straw tubes. The raw π^- momentum distribution related to high quality tracks is shown in Fig. 2a in a 1 MeV/c per bin distribution. A clear peak around 270 MeV/c is visible and it is the indication of the presence of ${}^7_\Lambda$Li formation, given the binding energy of the ${}^7_\Lambda Li$ ground state (5.58 ± 0.03 MeV [8]) and the excitation energies measured via γ-spectroscopy ([5–7] and references therein). Indeed the emerging π^- brings with it the information about the nuclear energy level of the ${}^7_\Lambda Li$ hypernucleus. Measuring the pion momentum with the experimental apparatus and considering the energy and the momentum conservation for the reaction $K^-_{stop} + {}^7Li \rightarrow {}^7_\Lambda Li + \pi^-$, one can get the hypernucleus mass in the specific level:

$$m_{Hyp,i} = \sqrt{(m_{K^-} + m_{{}^7Li} - E_{\pi,i})^2 - p^2_{\pi,i}}$$

where m_{K^-} is the K^- mass, $m_{{}^7Li}$ is the target nucleus ground state mass, $m^2_{Hyp,i}$ the mass of the particular ${}^7_\Lambda$Li hypernucleus formed in the ith energy level state, $p_{\pi,i}$ is the pion momentum for the produced hypernucleus level and $E_{\pi,i}$ the corresponding pion total energy. In general, in the literature, the Λ binding energy $B_{\Lambda,i}$ is often used. It is defined by the relation $m_{Hyp,i} = m_{{}^7Li-1n} + m_\Lambda - B_{\Lambda,i}$ where $m_{{}^7Li-1n}$ indicates the mass of the hypernuclear core in its ground state and m_Λ the mass of the Λ particle. For the calculations of the nucleus masses the AME2003 table has been used ([9]). The binding energy of the signal region of Fig. 2a has been plotted with a finer binning (0.25 MeV/c per bin) and is shown in Fig. 2b. Two peaks emerge from the background revealing the presence of at least two ${}^7_\Lambda$Li hypernucleus states.

The hypernuclear formation is not the only way a stopping kaon inside a ^{7}Li target can produce an emerging negative pion. Indeed there are quite a few reactions, some of them able to generate a π^- with a momentum distribution that can overlap with the one of hypernuclear formation. These reactions have been generated by the FINUDA Monte Carlo and reconstructed with the FINUDA reconstruction program in order to account for the background of our hypernuclear signal.

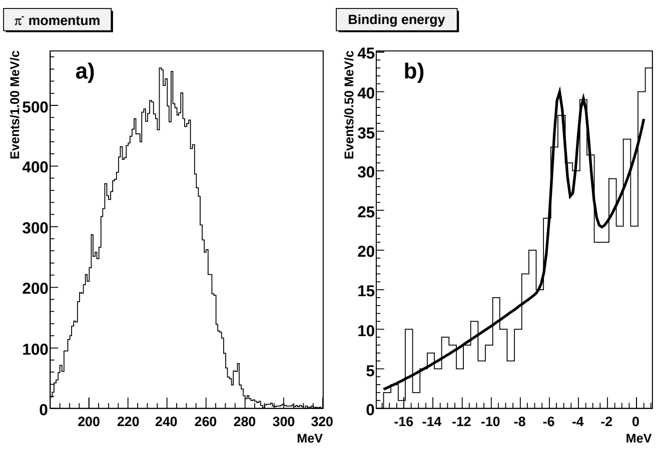

Fig. 2. ^{7}Li target spectrum as a function of: (a) π^- momentum; (b) B_Λ binding energy in the signal region. The superimposed fit, with a reduced χ^2 of 1.2, is the sum of two Gaussians and a model for the background (see text for details).

Another process that proved to be a background for the FINUDA hypernuclear data is the in-flight K^- decay occurring after the trigger signal has been generated by the K^- in the TOFINO slab and before entering the target. The μ^- produced by such decay in the vicinity of the target can be reconstructed as a π^- and can give an entry in the signal region. After a detailed MC analysis, the processes that demonstrated to contribute effectively as a background were the following: (1) the $K^-n \rightarrow \Lambda\pi^-$ reaction, (2) the $K^-(NN) \rightarrow \Sigma^-N$ reaction followed by $\Sigma^- \rightarrow n\pi^-$ and (3) the K^- in-flight decay. The first reaction (1), the quasi-free Λ production showed a contribution in the bound region ($B_\Lambda < 0$) due to reconstruction errors of the π^- momentum. The B_Λ distribution of the three reaction, in the region $-20 < B_\Lambda < 2$ MeV, have been fitted using a proper curve (exponential or polynomial) to model the background.

The experimental data have been thus fitted using the sum of the curves representing the three relevant background, and of two Gaussians, for the signal. The weight of the first two background reaction (1) and (2) have been left free to scale, while the weight of the K^- in-flight decay (3) has been fixed to the experimental value of the K^+ in-flight decay measured in the FINUDA data (same sample used for the signal extraction) corrected for the different reconstruction efficiencies. The width of the Gaussians have been fixed to the FINUDA resolution of 0.46 MeV (corresponding to 1.1 MeV FWHM). The result of the fit, with a reduced χ^2 of 1.2, for the binding energy distribution is superimposed in Fig. 2b. Two clear peaks are identified with the characteristics summarized in Tab. 1.

3.1 Binding energies

Using the fitting procedure described above, we find the two peaks at -5.33 ± 0.13 (*stat.*) MeV and at -3.68 ± 0.15 (*stat.*) MeV. The absolute scale of the momenta was determined with a precision better than 0.2 MeV/c [2], corresponding to ~ 0.18 MeV for the energy absolute scale. This value accounts for the systematic error.

The energy level scheme of ${}^7_\Lambda$Li is well known from Hyperball experiments [5,7]. This scheme gives the excitation energies from the ground state, measured to be at $B_\Lambda = -5.58 \pm 0.03$ [8]. This value has been calculated, having measured the π momentum, using the masses of the K^-, Λ and nuclei known in 1970 [10,11]. Taking into account all the corrections due to the changes of these masses, we can estimate that the ground state should be considered to be at -5.79 MeV.

Given the total error on the measurement (statistic and systematic), it becomes difficult to assert if the first (left) peak is due to the ground state, to the first excited state ($3/2^+$) or a mixture of the two. In the same way we cannot state if the second (right) peak is due to the $5/2^+$ state, to the $7/2^+$ state or a mixture of the two. The ΔB_Λ between the first and the second peak amounts to 1.69 MeV quite close to the ΔB_Λ between the ($5/2^+$) and the ($3/2^+$) states (see Fig. 1), but given the errors this cannot lead to certain conclusions. Summarizing, the two

${}^{7}_{\Lambda}Li$ hypernuclear states produced in FINUDA are belonging to the 1^+ and 3^+ ^{6}Li split doublets. Unfortunately, due to the FINUDA binding energy resolution, it is not possible to identify univocally the hypernuclear states inside such doublets.

This is the first time such hypernucleus states are so clearly visible, allowing the absolute binding energies to be determined using the π^- coming from the formation reaction. The limited statistics inhibit the search of other states and prevent a better evaluation of the produced states. The present FINUDA data taking will allow statistics of at least an order of magnitude larger to be recorded (a factor of two because of the use of two ^{7}Li targets and another factor 5 from the integrated luminosity) and a more detailed spectroscopic study to be performed.

3.2 Hypernuclear production rate

The measurement of an absolute rate of a reaction detected in an experimental apparatus is not, in general, a trivial task, since it implies an accurate determination of the apparatus acceptance as well as of trigger and reconstruction efficiencies for the reaction considered. The last quantities depend both on the detection efficiency of the different detectors and on the efficiency of the reconstruction algorithms. Inaccuracies in the determination of the previously mentioned factors affect directly the inferred value of the absolute production rates. Indeed, the hypernuclear production rate R_{hyp} per K^- stopped inside the target can be extracted from the following relation:

$$N_\pi^{hyp} = N_{K^-} \cdot R_{hyp} \cdot \epsilon_D \cdot \epsilon_\pi \qquad (1)$$

where N_π^{hyp} is the number of hypernuclei produced (Yield in Tab. 1), N_{K^-} the number of K^- stopped inside our ^{7}Li target (1.278.184), ϵ_D the efficiency in detecting the π track (correlated to detector efficiencies) and ϵ_π the efficiency in reconstructing the π^- (correlated to trigger bias, reconstruction algorithm and selection cuts). The ϵ_π can be accurately estimated by Montecarlo calculations whereas ϵ_D is affected by a large uncertainty.

Peak	$B_\Lambda \pm stat. \pm syst.$ (MeV)	Yield	Production rate (per K^- stop)
1	$-5.33 \pm 0.13\ \pm 0.18$	52 ± 11	0.47 ± 0.12 ‰
2	$-3.68 \pm 0.15\ \pm 0.18$	44 ± 10	0.39 ± 0.11 ‰

Table 1. Characteristics of the FINUDA ${}^{7}_{\Lambda}$Li states.

To elude such problem a more accurate procedure can be adopted in the FINUDA experiment, thanks to the abundant presence, in the recorded data, of the easily detected $K_{\mu2}$ decay process ($K^+ \to \mu^+\nu_\mu$), whose branching ratio is well known (BR($K_{\mu2}$)=63.44%[12]). Infact, this not only provides a physical reference rate to which the unknown hypernuclear rates can be referred, but also allows for the reduction of the systematic errors in the measurement described in the following. The number of detected and reconstructed μ^+ (N_{μ^+}) is correlated to the number of stopped K^+ inside the targets (N_{K^+}) by the relation $N_{\mu^+} = N_{K^+} \cdot \mathrm{BR}(K_{\mu2}) \cdot \epsilon_D \cdot \epsilon_\mu$, where ϵ_D is again related to the detector efficiency (being the same for μ^+ and π^-) and ϵ_μ, analogously to ϵ_π, is the efficiency in reconstructing the μ^+. Using the FINUDA MC, having fixed the hypernuclear production rate to $R_{hyp} = 0.1\%$, the ratio $\left(\frac{\epsilon_\mu}{\epsilon_\pi}\right)_{MC} = \left(\frac{N_{\mu^+} \cdot N_{K^-}}{N_\pi^{hyp} \cdot N_{K^+}} \cdot \frac{0.1\%}{\mathrm{BR}(K_{\mu2})} \cdot \frac{\epsilon_D}{\epsilon_D}\right)_{MC}$ could be calculated. Please note that in this way ϵ_D cancels away. This value, along with the number of μ^+ reconstructed in the data (15.337) and with the number of K^+ stopped inside the ^{7}Li target (1.277.004), has been used to determine the production rate according to the formula:

$$R_{hyp} = \frac{N_\pi^{hyp} \cdot N_{K^+}}{N_{\mu^+} \cdot N_{K^-}} \cdot \mathrm{BR}(K_{\mu2}) \cdot \left(\frac{\epsilon_\mu}{\epsilon_\pi}\right)_{MC} \qquad (2)$$

The production rate per K^- stopped has been thus measured to be 0.47 ± 0.12 $(stat.) \pm 0.11$ $(syst.)$ % for the first peak and 0.39 ± 0.11 $(stat.) \pm 0.11$ $(syst.)$ % for the second peak. It is the first time such hypernuclear production rates are measured for the $K^-_{stop} +^7 Li \to^7_\Lambda Li + \pi^-$ reaction.

4 Conclusions

FINUDA was able to produce, during his first short data taking period, ${}^{7}_{\Lambda}$Li hypernuclei using a complete new technique of stopping the K^- coming from the Φ decay inside a $e^+ - e^-$ collider machine (DAΦNE). The ${}^{7}_{\Lambda}$Li hypernuclear spectrum obtained (see Fig. 2) is the best up-to-date in a formation experiment with an energy resolution of 1.1 MeV (FWHM). The production rate for the identified hypernuclear states have been measured for the first time (see Tab. 1). Identification of hypenuclear states has been possible even with a limited statistics. These results are important also in light of the present FINUDA data taking when higher statistics will be available for a more detailed spectroscopic analysis and for studies of mesonic and non-mesonic decays.

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