Recent results on the weak decay of Λ hypernuclei

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The latest results from the FINUDA experiment on the Weak Decay of p-shell Λ-hypernuclei are presented and discussed. π^- spectra from mesonic decay were measured with magnetic analysis for the first time for ${}^{7}_{\Lambda}Li$, ${}^{9}_{\Lambda}Be$, ${}^{11}_{\Lambda}B$ and ${}^{15}_{\Lambda}N$. Branching ratio $\Gamma_{\pi^-}/\Gamma_{tot}$ were derived from the measured spectra. In addition spectra of protons from NMWD were obtained for ${}^{5}_{\Lambda}He$, ${}^{7}_{\Lambda}Li$, ${}^{9}_{\Lambda}Be$, ${}^{11}_{\Lambda}B$, ${}^{12}_{\Lambda}C$, ${}^{13}_{\Lambda}C$, ${}^{15}_{\Lambda}N$ and ${}^{16}_{\Lambda}O$. An estimation of the contributions of both Final State Interactions (FSI) and two-nucleon induced (2N) decay processes was performed, following a model independent approach. These results are confirmed by a new analysis of the triple coincidence (π^-, p, n) events.

1 Analysis method and results

The information coming from the study of the Λ-hypernuclei weak decay channels completes the knowledge on strange nuclear systems by spectroscopy, gained both by missing mass analyses and γ-ray measurements. Λ-hypernuclei decay through both mesonic (MWD) and non-mesonic weak decay (NMWD) processes. In MWD the Λ hyperon decays to a nucleon and a pion in the nuclear medium, similarly to the weak decay mode in free space:

$$\Lambda_{free} \rightarrow p + \pi^- + 37.8 \text{ MeV} \quad (64.2\%) \tag{1}$$

$$n + \pi^0 + 41.1 \text{ MeV} \quad (35.8\%) \tag{2}$$

in which the emitted nucleon (pion) carries a momentum $q \approx 100$ MeV/c. The theory of hypernuclear MWD was initiated by Dalitz [1, 2], and motivated by the observation of MWD reactions in the pioneering hypernuclear physics experiments with photographic emulsions. Following the development of counter techniques for use in (K^-, π^-) and (π^+, K^+) reactions on nuclei in the 1970s and 1980s, a considerable body of experimental data on Γ_{π^-} and/or Γ_{π^0} is now available on light Λ-hypernuclei up to ${}^{12}_{\Lambda}$C ([3] and references therein). As far as the NMWD is concerned, there are three decay channels:

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(3) $\quad {}^{A}_{\Lambda}\mathrm{Z} \rightarrow {}^{A-2}(\mathrm{Z}-1) + p + n \quad (\Gamma_p)$

(4) $\quad {}^{A}_{\Lambda}\mathrm{Z} \rightarrow {}^{A-2}\mathrm{Z} + n + n \quad (\Gamma_n)$

(5) $\quad {}^{A}_{\Lambda}\mathrm{Z} \rightarrow {}^{A-3}\mathrm{Z}' + N + N + N \quad (\Gamma_2)$

The channel (5) is known as two-nucleon induced (2N) decay and is due to the interaction of the Λ with a pair of strongly correlated nucleons; Z' stands for Z, $Z-1$ or $Z-2$ depending on the particular nucleons combination. The total NMWD rate of a Λ–hypernucleus is given by their sum: $\Gamma_{\mathrm{NMWD}} = \Gamma_p + \Gamma_n + \Gamma_2$. Several important experimental progresses in NMWD study have been made in the latest years but no experimental evidence has been obtained so far for the 2N induced decay. In the present work I report on measurements by the FINUDA experiment of MWD of hypernuclei in the p-shell comparing the measured π^- spectra and decay rates with the calculations by [4]. Furthermore I will describe two independent analyses of the NMWD of ${}^{7}_{\Lambda}Li$, ${}^{9}_{\Lambda}Be$, ${}^{11}_{\Lambda}B$, ${}^{12}_{\Lambda}C$, ${}^{13}_{\Lambda}C$, ${}^{15}_{\Lambda}N$ and ${}^{16}_{\Lambda}O$ hypernuclei which provided values for the 2N decay. The complete analysis and discussion of the results was already published in Ref. [5–7].

The results reported in the present paper have been obtained by analyzing the data collected by the FINUDA experiment, from 2003 to 2007 and correspond to an integrated luminosity of ~ 1.2 fb^{-1}. FINUDA is a fixed target experiment installed at one of the two interaction points of the DAΦNE e^+e^- ϕ–factory of Laboratori Nazionali di Frascati (INFN–Italy). Λ-hypernuclei are produced by means of the (K^-, π^-) reaction with K^-'s at rest by stopping in very thin targets the low energy ($\sim$ 16 MeV) K^-'s coming from the $\Phi \rightarrow K^-K^+$ decay channel. The analysis was performed on events collected out of ${}^{6}Li$, ${}^{7}Li$, ${}^{9}Be$, ${}^{12}C$, ${}^{13}C$ and (D_2O) targets. The experimental method is briefly described here, while full details are reported in [5–7]. To investigate the MWD process (1) all the events characterized by the presence of two π^-'s detected in coincidence were selected. One π^-, with a momentum as high as $260-290$ MeV/c, gives the signature of the formation of the ground-state of the hypernuclear system or of a low lying excited state decaying to it by electromagnetic emission. The second π^-, with a momentum lower than 115 MeV/c, gives the signature of the decay. The lower threshold for the detection momentum of these π^-'s is $\sim$ 80 MeV/c and their momentum resolution is Δp / p $\sim$ 6% FWHM at 110 MeV/c. The analysis of the NMWD was performed by selecting all the events with two particles emitted in coincidence: a π^- carrying the information of the hypernucleus formation and a proton coming from the same K^- interaction vertex, which gives the signature of the NMWD. Protons were identified with an efficiency of 90% and the proton energy resolution was ΔE/E$\sim$ 2% FWHM at 80 MeV. A further requirement was made asking for the detection of a neutron. The outer FINUDA detector, called TOFONE [7], a barrel of 72 scintillator slabs was used for trigger and P.I.D. (by Time Of Flight) of the charged particles and to detect even neutral ones with an efficiency of the order of 10% for neutrons in the range 15-150 MeV. The energy resolution on the neutron is $\sim$13% at 10 MeV and $\sim$10% at 100 MeV.

As far as the MWD is concerned, the π^- spectra allow to have a more careful confirmation of the elementary mechanism that is supposed to underlie the decay process, as well as to have information on the spin-parity of the initial hypernuclear ground state. In this respect the study of pion spectra from MWD can be regarded as an indirect spectroscopic investigation tool. Due to the π^- momentum detection threshold of the apparatus ($\sim$ 80 MeV/c), only MWD spectra of ${}^{7}_{\Lambda}Li$, ${}^{9}_{\Lambda}Be$, ${}^{11}_{\Lambda}B$ (${}^{12}C$ targets) and ${}^{15}_{\Lambda}N$ (${}^{16}O$ target) were investigated. Spectra from ${}^{12}_{\Lambda}$C and ${}^{16}_{\Lambda}$O could not be observed. The decay π^- momentum spectra show interesting structures whose meaning can be better understood by considering the corresponding kinetic energy spectra that are directly related to the excitation function of the daugther nucleus. Kinetic energy spectra, background subtracted and acceptance corrected, were evaluated for MWD of ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{11}_{\Lambda}$B and ${}^{15}_{\Lambda}$N. Based on these measurements, the spin-parity assignment $1/2^+$ for ${}^{7}_{\Lambda}$Li and $5/2^+$ for ${}^{11}_{\Lambda}$B ground-state were confirmed. The ground-state spin of ${}^{15}_{\Lambda}$N has not been determined experimentally and the most recent theoretical study of Λ-hypernuclear spin dependence predicts $J^{\pi}({}^{15}_{\Lambda}\mathrm{N}_{g.s.}) = 3/2^+$. The shape of the measured spectrum slightly favors $J^{\pi}({}^{15}_{\Lambda}\mathrm{N}_{g.s.}) = 3/2^+$ with respect of $1/2^+$ and considering the total MWD rate it was possible to determine for the first time the ${}^{15}_{\Lambda}\mathrm{N}_{g.s.}$ spin parity. For the full discussion of the interpretation of the ${}^{15}_{\Lambda}$N spectrum see [5]. The values of the branching ratios of the MWD reaction was also evaluated for the studied hypernuclei and they are reported in Fig. 1. It is remarkable that a very good agreement holds among the present results and previous measurements, when existing, and among the present results and theoretical calculations. Very strong nuclear structure effects are also evident.

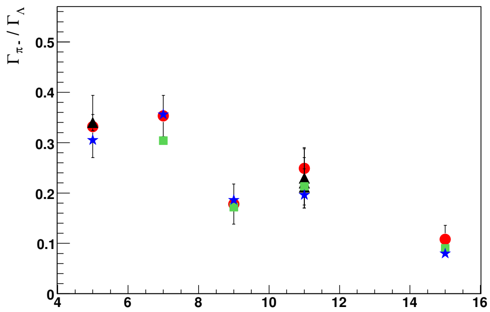

Figure 1: Total π^- decay rate Γ_{π^-} in units of Γ_Λ as a function of the hypernuclear mass number A. Open circles: ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{11}_{\Lambda}$B and ${}^{15}_{\Lambda}$N values measured by FINUDA [5]; ${}^{5}_{\Lambda}$He is also reported for sake of completeness. Full triangles: previous measurements; open squares: theoretical calculations from [8]; full stars: theoretical calculation from [4].

With regard to the NMWD study, in Fig. 2 the kinetic energy spectra of protons coming from the NMWD of ${}^{5}_{\Lambda}He$, ${}^{7}_{\Lambda}Li$, ${}^{9}_{\Lambda}Be$, ${}^{11}_{\Lambda}B$, ${}^{12}_{\Lambda}C$, ${}^{13}_{\Lambda}C$, ${}^{15}_{\Lambda}N$ and ${}^{16}_{\Lambda}O$ are shown. All the spectra are background subtracted and acceptance corrected; the errors in the spectra are statistical only and include both the contributions from background subtraction and acceptance correction. We estimated a systematic error of less than 5%. Even though affected by considerable errors, in particular in the low energy region, the proton kinetic energy spectra show a clear trend as a function of the hypernuclear mass number A (from 5 to 16): a peak around 80

MeV (which corresponds to about half of the Q–value for the free $\Lambda p \to np$ reaction) is broadened by the Fermi motion of nucleons and more and more blurred as A increases. The peak is smeared, on its low energy side, by a rise that can be ascribed to FSI and two–nucleon induced weak decays.

To estimate the contribution of this last channel each proton spectrum from 80 MeV onwards was fitted by a Gaussian function. It was assumed that the proton spectrum beyond the peak mean value is due to protons coming from the $\Lambda p \to np$ reaction and that the 2N channel can be neglected in this region (A_{high}). On the contrary, the spectrum below the peak mean value is fed by protons from both $\Lambda p \to np$ and 2N decays and is also affected by FSI (A_{low}). The determination of the 2N decay was based on two assumptions: the first one is that the two–nucleon induced NMWD is dominated by the $\Lambda np \to nnp$ channel ($\Gamma_2 = \Gamma(\Lambda np \to nnp) + \Gamma(\Lambda pp \to npp) + \Gamma(\Lambda nn \to nnn) \equiv \Gamma_{np} + \Gamma_{pp} + \Gamma_{nn} \simeq \Gamma_{np}$) since the recent microscopical calculation of Ref. [12] quote $\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$ and the second one stands on a constant Γ_2/Γ_p ratio for the considered hypernuclear mass range.

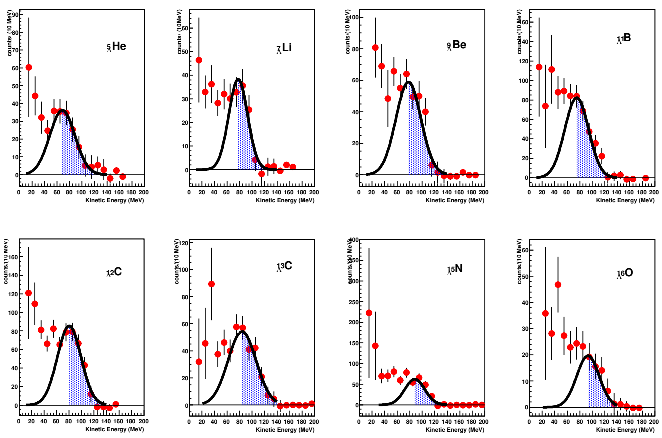

Figure 2: Proton kinetic energy spectra from the NMWD of (from left to right): ${}^{5}_{\Lambda}He$, ${}^{7}_{\Lambda}Li$, ${}^{9}_{\Lambda}Be$, ${}^{11}_{\Lambda}B$, ${}^{12}_{\Lambda}C$, ${}^{13}_{\Lambda}C$, ${}^{15}_{\Lambda}N$ and ${}^{16}_{\Lambda}O$. The blue filled area is the spectrum area in which the two–nucleon induced NMWD is negligible.

Consider now the ratio:

$$R \equiv \frac{A_{\rm low}}{A_{\rm low} + A_{\rm high}} = \frac{0.5 + \dfrac{\Gamma_2}{\Gamma_p}}{1 + \dfrac{\Gamma_2}{\Gamma_p}} + bA \,. \tag{6}$$

In Fig. 3 the experimental values of this ratio are plotted as a function of A.

Following a model independent analysis, fully described in [6] a value of $\Gamma_2/\Gamma_p = 0.43 \pm 0.25$ was determined. As discussed in [6], to determine $\Gamma_2/\Gamma_{\rm NMWD}$ the Γ_n/Γ_p ratio needs to be

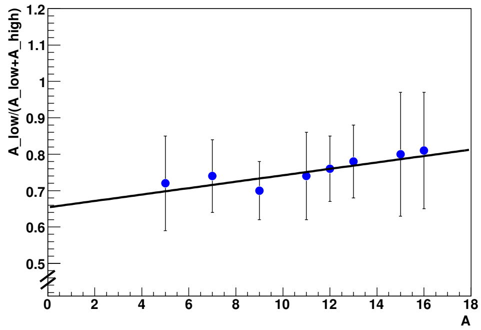

Figure 3: The ratio $A_{\mathrm{low}}/(A_{\mathrm{low}} + A_{\mathrm{high}})$ as a function of the hypernuclear mass number.

known. Using recent experimental results [9] for ${}^{5}_{\Lambda}H$ and for ${}^{12}_{\Lambda}C$ together with the above determination of Γ_2/Γ_p one obtains $\Gamma_2/\Gamma_{\mathrm{NMWD}} = 0.24 \pm 0.10$.

In a following analysis of the events with a triple (π^-, n, p) coincidences a neutron was required in addition. We also fixed for each hypernucleus a proton energy threshold E_p=20 MeV below the Gaussian mean value μ found in [6]. We verified that this value was the best compromise on the signal/background ratio and furthermore we chose a threshold for the angular correlation between the neutron and the proton of cosθ(np)=-0.8.
We analized then the triple coincidence (π^-, n, p) selecting alla the events with E_p lower than the threshold and cosθ(np)>-0.8. These events correspond mainly to the $\Lambda np \rightarrow nnp$ process with a small contribution of FSI. Fig. 4 shows the dependence on the mass number A of the selected events divided by the number of protons with $E_p \geqslant \mu$; the above number should be proportional to Γ_{np} and Γ_p respectively.

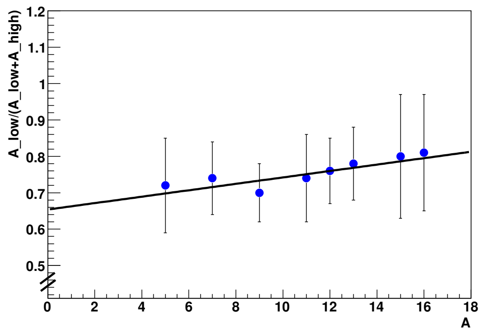

Figure 4: The ratio $N_{\mathrm{n}}/N_{\mathrm{p}}$ as a function of the hypernuclear mass number A.

Following the same assumpion of [6] we found $\Gamma_{np}/\Gamma_p = 0.39 \pm 0.16_{stat}{}^{+0.04_{sys}}_{-0.03_{sys}}$. Using the experimental value of Γ_n/Γ_p reported in [9] for ${}^{5}_{\Lambda}He$ and ${}^{12}_{\Lambda}C$ and our determination of Γ_{np}/Γ_p we obtain $\Gamma_{2N}/\Gamma_{\rm NMWD} = 0.21 \pm 0.07_{stat}{}^{+0.03_{sys}}_{-0.02_{sys}}$. This value supports the latest theoretical predictions [14] ($\Gamma_2/\Gamma_{\rm NMWD}$=0.26), the recent experimental results of [11] (0.29 ± 0.13) and the previous FINUDA result [6], but bears a smaller error. Calculating the mean of the experimental determinations [7,11] of $\Gamma_{2N}/\Gamma_{\rm NMWD}$ at our disposal one found that the contribution of the two–nucleon induced decay is 0.25 ± 0.15.

2 Conclusions

The FINUDA experiment has performed a systematic study of MWD and NMWD charged particles spectra of Λ–hypernuclei in the $A = 5 \div 16$ mass range. From the study of the kinetic energy spetra of π^- the spin-parity assignment $J^\pi({}^{15}_{\Lambda}{\rm N}_{g.s.}) = 3/2^+$ was made. The proton spectra from the NMWD were also analyzed and an evaluation of the nucleon FSI effects and of the 2N decay contribution to the NMWD process was performed: an experimental value of $\Gamma_2/\Gamma_{NMWD} = 0.24 \pm 0.10$ was obtained. This result was confirmed in the analysis of the triple (π^-, n, p) coincidence, with a reduction of the error and leading to an estimate of Γ_2/Γ_{NMWD}=$0.21 \pm 0.07_{stat}{}^{+0.03_{sys}}_{-0.02_{sys}}$

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