

Study of the two-nucleon induced Non Mesonic Weak Decay with FINUDA

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Abstract. The latest results from the FINUDA experiment on the Non-Mesonic Weak Decay (NMWD) channels of p-shell Λ -hypernuclei are presented and discussed. Spectra of protons from NMWD were obtained for ${}^5_\Lambda\text{He}$, ${}^7_\Lambda\text{Li}$, ${}^9_\Lambda\text{Be}$, ${}^{11}_\Lambda\text{B}$, ${}^{12}_\Lambda\text{C}$, ${}^{13}_\Lambda\text{C}$, ${}^{15}_\Lambda\text{N}$ and ${}^{16}_\Lambda\text{O}$. 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. The previously published results are confirmed by a new analysis of the triple coincidence (π^- , p, n) events.

1. Introduction

The information coming from the study of the Λ -hypernuclei weak decay channels completes the knowledge on strange nuclear systems, gained both by missing mass analyses and γ -ray spectroscopy measurements (see [1] for a complete review). Λ -hypernuclei decay through both

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mesonic (MWD) and non-mesonic weak decay (NMWD) processes. As far as the NMWD is concerned, there are three decay channels:

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

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

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

The channel (3) 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: $\Gamma_{\text{NMWD}} = \Gamma_p + \Gamma_n + \Gamma_2$. NMWD of Λ -hypernuclei has been studied quite extensively both experimentally and theoretically [2, 3] since the early days of hypernuclear physics; indeed, it is basically the way to get information on the baryon-baryon strangeness-changing weak interactions (for reviews see [4, 5]). Several important experimental progresses in NMWD study have been made in the latest years, allowing more precise values for Γ_n and Γ_p decay rates to be obtained and the long-standing puzzle on the Γ_n/Γ_p ratio [6] to be solved. Nevertheless, no experimental evidence has been obtained so far for the 2N induced decay, with the exception of three indirect results [7, 8, 9], while various theoretical papers were dedicated to the calculation of the rates and the nucleon spectra for this channel [10, 11, 12, 13, 14, 15]; they foresee a significant contribution of the 2N induced decay to the total NMWD rate. The FINUDA experiment performed a complete analysis of the protons from NMWD of ${}^5_{\Lambda}\text{He}$, ${}^7_{\Lambda}\text{Li}$, ${}^9_{\Lambda}\text{Be}$, ${}^{11}_{\Lambda}\text{B}$, ${}^{12}_{\Lambda}\text{C}$, ${}^{13}_{\Lambda}\text{C}$, ${}^{15}_{\Lambda}\text{N}$ and ${}^{16}_{\Lambda}\text{O}$ hypernuclei. The complete analysis and discussion of the results was already published in Ref. [17]. Here an extension of that analysis is also reported, in which an additional neutron from the NMWD is detected. The results, found in this analysis, are compatible with the previous ones within the errors. Using in both the analyses a model independent method we extracted the contribution of FSI and of the 2N induced decay channel to the total NMWD rate.

2. Analysis technique

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 $\sim 1.2 \text{ fb}^{-1}$. FINUDA is a fixed target experiment installed at one of the two interaction points of the DAΦNE $e^+e^- \phi$ -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 ($\sim 16 \text{ MeV}$) K^- 's coming from the $\Phi \rightarrow K^- K^+$ decay channel. The analysis was performed on events collected out of ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^9\text{Be}$, ${}^{12}\text{C}$, ${}^{13}\text{C}$ and O_2 (D_2O) targets. The experimental method is briefly described here, while full details are reported in [17]. A detailed description of the experimental apparatus can be found in [18]. The analysis of the NMWD, published in [17], was performed by selecting all the events with two particles emitted in coincidence: a π^- carrying the information of the hypernucleus formation (in its ground state or in a low lying excited state decaying electromagnetically) and a proton coming from the same K^- interaction vertex, which gives the signature of the NMWD. The binding energy intervals selected to identify the formation of the different hypernuclei under study are reported in Table 1 of Ref.[17]. Protons were identified by means of both the specific energy loss in the charge sensitive detectors of the FINUDA apparatus and, if present, by the mass identification from the time-of-flight system; the particle identification efficiency was higher than 90%.

A further requirement was made asking for the detection of a neutron. FINUDA was a magnetic spectrometer well optimized for the detection and measurement of charged particles, with an angular coverage of $2\pi \text{ sr}$ [18]. It was not optimised for neutral particles detection (γ, π^0, n).

However the outer FINUDA detector, called TOFONE [17, 18], a barrel of 72 scintillator slabs (255 cm long and 10 cm thick), used for trigger and P.I.D. (by Time Of Flight) of the charged particles and to detect even neutral with an efficiency of the order of 10% for neutrons in the range 15-150 MeV.

Neutrons were identified looking for the TOFONE elements not connected to curve trajectories of charged particles crossing the FINUDA tracking system sector facing the fired TOFONE slabs. A selection on β helps discriminating neutron signals from γ 's, produced abundantly from π^0 decay. A cut on the $1/\beta$ value was adopted, requiring $1/\beta \geq 1.47$, to eliminate the γ peak at $\beta=1$. The cleanest way to identify neutrons from NMWD is to tag them by the proton emitted in coincidence. The precision on the determination of the impact point on the scintillator was 5 cm FWHM. Combining this value with the timing resolution of 700 ps FWHM (all slabs), obtained by fitting the γ 's peak of the TOF distribution, we finally obtained for the energy resolution on the neutron $\sim 13\%$ at 10 MeV and $\sim 10\%$ at 100 MeV.

3. NMWD results

3.1. Proton spectra analysis

Proton spectra were obtained in coincidence with a π^- signalling the formation of ${}^5_\Lambda\text{He}$, ${}^7_\Lambda\text{Li}$, ${}^9_\Lambda\text{Be}$, ${}^{11}_\Lambda\text{B}$, ${}^{12}_\Lambda\text{C}$, ${}^{13}_\Lambda\text{C}$, ${}^{15}_\Lambda\text{N}$ and ${}^{16}_\Lambda\text{O}$ [16, 17].

Background is due to the $K^-(np) \rightarrow \Sigma^- p$ absorption on two correlated nucleons in the absorbing nucleus, followed by the $\Sigma^- \rightarrow \pi^- n$ decay. This background was simulated, reconstructed and subdued to the same analysis chain used for the real data and subtracted from the raw proton spectra.

All the measured spectra have similar shape and show a clear trend as a function of the hypernuclear mass number A (from 5 to 16): a bump around 80 MeV (about half of the Q -value for the free $\Lambda p \rightarrow np$ reaction) broadened by the Fermi motion of nucleons and more and more blurred as A increases. The bump presents, on its low energy side, a rise that can be ascribed to FSI and 2N weak decays. To estimate the contribution of this channel each proton spectrum from 80 MeV onwards was fitted by a Gaussian function. It was assumed that the part of the proton spectrum beyond the peak mean value is due to protons coming from the $\Lambda p \rightarrow np$ reaction and that the 2N channel can be neglected in this region, following [13]. On the contrary, the part of spectrum below the peak mean value is fed by protons from both $\Lambda p \rightarrow np$ and 2N decays and is also affected by FSI. Let then denote with $N_p^{\text{FSI-low}}$ ($N_p^{\text{FSI-high}}$) the difference between the number of protons detected in the region below (beyond) the peak of the spectrum and the number of primary protons which originates from one- and two-nucleon induced weak decays in the same region. According to the above assumptions and definitions, for the total number of protons A_{low} in the low energy region and A_{high} in the high energy region one has:

$$A_{\text{low}} = N(\Lambda p \rightarrow np)/2 + N(\Lambda np \rightarrow nnp) + N_p^{\text{FSI-low}}, \quad (4)$$

$$A_{\text{high}} = N(\Lambda p \rightarrow np)/2 + N_p^{\text{FSI-high}}, \quad (5)$$

where $N(\Lambda p \rightarrow np)$ is the total number of $\Lambda p \rightarrow np$ decays and $N(\Lambda np \rightarrow nnp)$ is the total number of $\Lambda np \rightarrow nnp$ decays (occurring only in the A_{low} part) contributing to the spectra. One can also write:

$$\frac{N(\Lambda np \rightarrow nnp)}{N(\Lambda p \rightarrow np)} = \frac{\Gamma_{np}}{\Gamma_p} \simeq \frac{\Gamma_2}{\Gamma_p}. \quad (6)$$

Note that in Eq. (4) and in the last equality of Eq. (6) the two-nucleon induced NMWD has been assumed to be dominated by the $\Lambda np \rightarrow nnp$ channel: $\Gamma_2 = \Gamma(\Lambda np \rightarrow nnp) + \Gamma(\Lambda pp \rightarrow npp) + \Gamma(\Lambda nn \rightarrow nnn) \equiv \Gamma_{np} + \Gamma_{pp} + \Gamma_{nn} \simeq \Gamma_{np}$, since the recent microscopical calculation of

Ref. [15] quote $\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$. The experimental values of the ratio

$$R \equiv \frac{A_{\text{low}}}{A_{\text{low}} + A_{\text{high}}} = \frac{0.5N(\Lambda p \rightarrow np) + N(\Lambda np \rightarrow nnp) + N_p^{\text{FSI-low}}}{N(\Lambda p \rightarrow np) + N(\Lambda np \rightarrow nnp) + N_p^{\text{FSI-low}} + N_p^{\text{FSI-high}}} \quad (7)$$

are plotted as a function of A in Fig. 1. Due to FSI effects, both A_{low} and A_{high} are expected to be proportional to A : one can thus perform a fit of the data with a function $R(A) = (a' + b'A)/(c' + d'A)$. It turns out that $d'/c' \leq 10^{-3}$, thus just a linear fit, $R(A) = a + bA$, can be considered. The result of such a fit ($a = 0.654 \pm 0.138$, $b = 0.009 \pm 0.013$ and $\chi^2/ndf = 0.298/6$) is shown in Fig. 1. By introducing the hypothesis of a constant Γ_2/Γ_p ratio for the considered hypernuclear mass range, one can rewrite Eq. (7) as:

$$R(A) = \frac{0.5 + \frac{\Gamma_2}{\Gamma_p}}{1 + \frac{\Gamma_2}{\Gamma_p}} + bA. \quad (8)$$

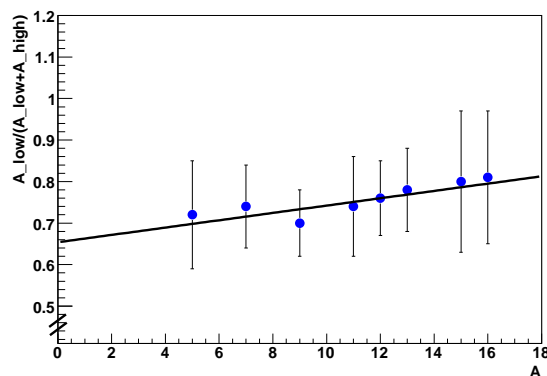


Figure 1. The ratio $A_{\text{low}}/(A_{\text{low}} + A_{\text{high}})$ as a function of the hypernuclear mass number A .

Eq. (8) can be solved for Γ_2/Γ_p for each hypernucleus. The values obtained for Γ_2/Γ_p for the hypernuclei are compatible one with each other within errors. Thus the final result can be given by the weighted average:

$$\frac{\Gamma_2}{\Gamma_p} = 0.43 \pm 0.25. \quad (9)$$

As discussed in [17], to determine $\Gamma_2/\Gamma_{\text{NMWD}}$ the Γ_n/Γ_p ratio needs to be known. Using recent experimental results [7] for ${}^5_\Lambda\text{H}$ and for ${}^{12}_\Lambda\text{C}$ together with the above determination of Γ_2/Γ_p one obtains:

$$\frac{\Gamma_2}{\Gamma_{\text{NMWD}}} = 0.24 \pm 0.10. \quad (10)$$

This value supports both theoretical predictions [11, 12, 13, 14, 15] and the latest experimental results of Ref. [7, 8, 9].

3.2. Triple coincidence analysis

We notice that the large error of the result of Ref. [17] is due to the adopted analysis procedure, in which all the errors relevant to the different regions of the spectra had to be taken into account. In the 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 [17]. We verified that this value was the best compromise on the signal/background ratio and furthermore we chose a threshold for angular correlation between the neutron and the proton such as $\cos\theta(np)=-0.8$.

We classified then the triple coincidence (π^- , n, p) events according to:

- (i) events with E_p larger than the threshold and $\cos\theta(np)\leq-0.8$. These events correspond mainly to the ($\Lambda p \rightarrow np$) process without FSI on the proton. The expected energy and angular distribution are such that the contribution from the $\Lambda np \rightarrow nnp$ process is at the 5% level;
- (ii) events with E_p larger than the threshold and $\cos\theta(np)>-0.8$. These events correspond mainly to the ($\Lambda p \rightarrow np$) process with FSI on the neutron. The expected proton energy distribution are such that the contribution from the $\Lambda np \rightarrow nnp$ process is about 10%;
- (iii) events with E_p lower than the threshold and $\cos\theta(np)\leq-0.8$. These events correspond mainly to the $\Lambda p \rightarrow np$ process with FSI on the proton. The expected contribution from $\Lambda np \rightarrow nnp$ is less than 10%;
- (iv) events with E_p lower than the threshold and $\cos\theta(np)>-0.8$. These events correspond mainly to the $\Lambda np \rightarrow nnp$ process with a small contribution of FSI.

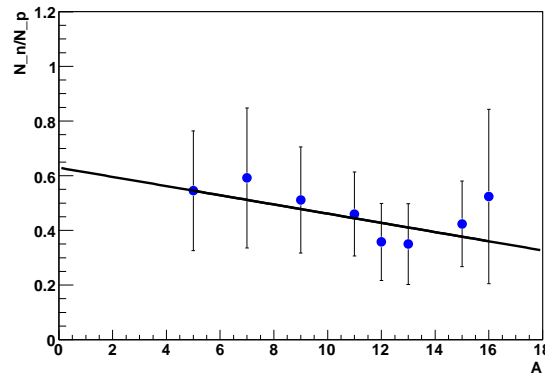


Figure 2. The ratio N_n/N_p as a function of the hypernuclear mass number A .

As pointed out in Ref.[17] the two-nucleon induced NMWD can be assumed to be dominated by the $\Lambda np \rightarrow nnp$ channel. Consider now the ratio:

$$R' \equiv \frac{N_n(E_p \leq \text{threshold}, \cos\theta(np) > -0.8)}{N_p(E_p > \mu)} = \frac{N(\Lambda np \rightarrow nnp) + FSI_{1N} + FSI_{2N}}{0.5N(\Lambda p \rightarrow np) + FSI_{1N}} \quad (11)$$

where $N_n(E_p \leq \text{threshold}, \cos\theta(np) > -0.8)$ is the number of neutrons fulfilling the condition iv), $N_p(E_p > \mu)$ is the number of protons with an energy larger than the mean value of the fit reported in [17] and FSI_{1N} and FSI_{2N} are, respectively, the final state interaction contributions due to the one- and two-nucleon induced NMWD. In Fig. 2 the experimental value of this ratio for each hypernucleus is plotted as a function of A . Due to FSI both

$N_n(E_p \leq \text{threshold}, \cos\theta(np) > -0.8)$ and $N_p(E_p > \mu)$ are expected to be proportional to A ; we performed a fit with a function $R(A) = (a' + b'A)/(c + dA)$ and we found $d/c \leq 10^{-3}$. This result give us the possibility to consider a linear fit $R(A) = (a + bA)$ of the ratio (11). The result of such a fit ($a = 0.629 \pm 0.253$, $b = -0.017 \pm 0.021$ and $\chi^2/ndf = 0.902/6$) is reported in fig. 2. As assumed in Ref.[17] Γ_{2N}/Γ_p is constant in the mass number range considered in this analysis and therefore eq.(11) can be rewritten as:

$$R(A) \equiv \frac{\Gamma_{2N}}{0.5\Gamma_p} + bA, \quad (12)$$

which can then be solved for Γ_2/Γ_p for each hypernucleus, obtaining:

$$\frac{\Gamma_{2N}}{\Gamma_p} = \frac{[R(A) - bA]}{2}. \quad (13)$$

The values obtained for Γ_{2N}/Γ_p are, like in the proton spectra analysis, for all the studied hypernuclei compatible one with each other within errors. The final result can thus be given by their weighted average: $\Gamma_{2N}/\Gamma_p = 0.33 \pm 0.07$. This value is lower than the one in [17] but compatible within the errors. The error quoted here is less than half of that one reported in [17]. To determine $\Gamma_{2N}/\Gamma_{NMWD}$, the same method used in [17] can be applied: $\Gamma_2/\Gamma_{NMWD} = 0.18 \pm 0.03$.

4. Conclusions

The FINUDA experiment has performed a systematic study of NMWD of Λ -hypernuclei in the $A = 5$ –16 mass range. NMWD proton spectra have been obtained for ${}^5_\Lambda\text{He}$, ${}^7_\Lambda\text{Li}$, ${}^9_\Lambda\text{Be}$, ${}^{11}_\Lambda\text{B}$, ${}^{12}_\Lambda\text{C}$, ${}^{13}_\Lambda\text{C}$, ${}^{15}_\Lambda\text{N}$ and ${}^{16}_\Lambda\text{O}$. An evaluation of the nucleon FSI effects and of the 2N decay contribution to the NMWD process was performed: a linear dependence of FSI on the hypernuclear mass number A was found and an experimental value of the ratio $\Gamma_2/\Gamma_p = 0.43 \pm 0.25$ was obtained for the first time, leading to an estimate of Γ_2/Γ_{NMWD} of about 24%. These results were confirmed in the analysis of the triple (π^- , n, p) coincidence, with a reduction of more than a factor two of the relative error.

5. References

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