



Neutron–proton coincidences from Non-Mesonic Weak Decay of p-shell Λ -hypernuclei and determination of the two-nucleon induced process [☆]

FINUDA Collaboration

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ABSTRACT

The decay of Λ -hypernuclei without π emission, known as Non-Mesonic Weak Decay (NMWD), gives an effective tool to investigate $\Delta S = 1$ four-baryon interactions. It was theoretically suggested that the two-nucleon induced mechanism could play a substantial role in reproducing the observed NMWD decay rates and nucleon spectra, but at present no direct evidence of such a mechanism has been obtained. The FINUDA experiment, exploiting the possibility to detect both charged and neutral particles coming from the hypernucleus decay, has allowed us to deduce the relative weight of the two nucleon induced decay rate to the total NMWD rate. The value of $\Gamma_{2N}/\Gamma_{\text{NMWD}} = 0.21 \pm 0.07_{\text{stat}}^{+0.03_{\text{sys}}} - 0.02_{\text{sys}}$ has been deduced, well consistent with the previous determinations.

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[☆] We dedicate this Letter to the memory of Dr. Ambrogio Pantaleo passed away prematurely on June 23rd, 2010. Dr. Pantaleo participated very actively since the beginning to the FINUDA experiment, taking particular care of the neutron detection, on which the present analysis is based.

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1. Introduction

The Non-Mesonic Weak Decay (NMWD) of hypernuclei has stimulated a strong interest since the beginning of hypernuclear physics [1]. Indeed it has been realized that the two channels of NMWD,

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

and

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

where A and Z indicate, respectively, the mass and atomic numbers of the decaying systems, are due to the occurrence of the two weak reactions:

$$\Lambda p \rightarrow np \quad (\Gamma_p) \quad (3)$$

and

$$\Lambda n \rightarrow nn \quad (\Gamma_n) \quad (4)$$

inside nuclei. These two decay processes are usually referred to as “one-proton induced NMWD” and, respectively, “one-neutron induced NMWD” of Λ -hypernuclei. Reactions (3) and (4) constitute a unique class of four-baryon, strangeness non-conserving weak interactions and the determination of their rates is of considerable interest. These rates cannot be determined experimentally by the direct reactions (3) and (4), due to the lack of suitable beams of hyperons. The only way is to study them through their occurrence in hypernuclei (reactions (1) and (2)).

Unfortunately, also this last approach is not experimentally easy, due to the low rate of production of Λ -hypernuclei in ground or excited states and to the detection efficiency of neutrons, which is small despite the large acceptance and good energy resolution apparatuses; moreover the model dependence of the analysis remains an issue. For these reasons the experimental progress in this field has been limited for many years, in contrast to the vivid development of many theoretical approaches. Recent reviews can be found in [2] and [3]. Ref. [4] first pointed out the possibility that a considerable amount of the strength for NMWD, up to about 20% of the total decay width, could be accounted for by the interaction of a Λ with a pair of correlated nucleons in a nucleus, such as:

$$\Lambda np \rightarrow nnp \quad (\Gamma_{np}), \quad (5)$$

$$\Lambda pp \rightarrow npp \quad (\Gamma_{pp}), \quad (6)$$

$$\Lambda nn \rightarrow nnn \quad (\Gamma_{nn}), \quad (7)$$

referred to in the following as $2N$ -induced NMWD. The total non-mesonic rate is given by $\Gamma_{\text{NMWD}} = \Gamma_{1N} + \Gamma_{2N}$, with $\Gamma_{1N} = \Gamma_n + \Gamma_p$ and $\Gamma_{2N} = \Gamma_{np} + \Gamma_{pp} + \Gamma_{nn}$.

In addition to reaction (3), (4), (5), (6) and (7), for light hypernuclei one can also study the so-called rare two-body decay. Recently FINUDA has been able to measure the decay yields and the branching ratios of the two-body decay channels ${}^4_\Lambda\text{He} \rightarrow d + d$, ${}^4_\Lambda\text{He} \rightarrow p + t$ and ${}^5_\Lambda\text{He} \rightarrow d + t$ [5].

The suggestion of the existence of the $2N$ -induced NMWD was followed by detailed calculations thus stimulating a big experimental effort on the subject. A first summary of the theoretical issues can be found in [2], whereas [6] ([7]) reports the latest developments in the calculation of the NMWD widths (nucleon spectra). First experimental determinations of Γ_{2N} were done by indirect methods based on the fit of the ${}^{12}_\Lambda\text{C}$ experimental inclusive proton spectra using IntraNuclear Cascade (INC) calculations including $2N$ -induced NMWD [8] and reported for the $\Gamma_{2N}/\Gamma_{\text{NMWD}}$ ratio a value as large as 40%.

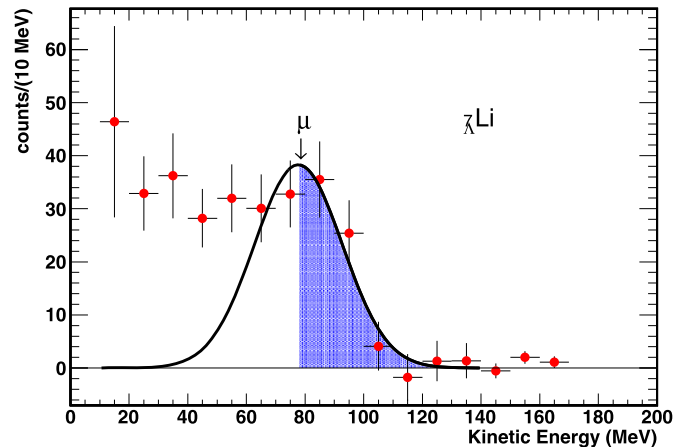


Fig. 1. Proton kinetic energy from the NMWD of ${}^7_\Lambda\text{Li}$ extracted from Fig. 1 of [10].

Coincidence measurements of neutrons and protons, with an energy threshold of 30 MeV, following ${}^{12}_\Lambda\text{C}$ NMWD were recently analyzed taking into account the angular correlations between the detected nucleons [9]. The coincidence spectra were analyzed using a new version of the INC code, with a strength varied to fit the ${}^{12}_\Lambda\text{C}(p, p')$ total inelastic cross section, in order to account for the effect of the Final State Interaction (FSI) on the experimental spectra. From this analysis the experimental value $\Gamma_{2N}/\Gamma_{\text{NMWD}} = 0.29 \pm 0.13$ was reported for ${}^{12}_\Lambda\text{C}$ [9].

A different approach to extract the strength for the $2N$ -induced NMWD was followed by the FINUDA Collaboration [10]. Proton energy spectra 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 ${}^{16}_\Lambda\text{O}$ were measured with good resolution ($\Delta p/p = 2\%$ FWHM for protons of 80 MeV) and with a kinetic energy detection threshold of 15 MeV. All the measured spectra showed a similar behaviour, i.e., a bump at about 80 MeV, roughly at the energy expected from reaction (1). The bump is quite well defined in the high energy portion, whereas at low energies it is blurred in a continuum generated by FSI and superimposed to the $2N$ -induced NMWD contribution; as example the spectrum of ${}^7_\Lambda\text{Li}$ from [10] is reported in Fig. 1. Under very simple hypotheses, the contributions from FSI and $2N$ -induced NMWD were disentangled, providing: $\Gamma_{2N}/\Gamma_p = 0.43 \pm 0.25$ and $\Gamma_{2N}/\Gamma_{\text{NMWD}} = 0.24 \pm 0.10$.

In this Letter we present a different approach, made possible by the detection of both proton and neutron in coincidence, by which we determine the value of $\Gamma_{2N}/\Gamma_{\text{NMWD}}$.

2. The experimental and analysis method

The data were collected by the FINUDA experiment, installed at one of the two interaction regions of the DAΦNE (e^+, e^-) ϕ -factory of Laboratori Nazionali di Frascati (INFN, Italy) and correspond to an integrated luminosity of about 1.2 fb^{-1} . A detailed description of the FINUDA experiment can be found in [11,12].

We do not report here experimental and analysis details already described in [10] and references therein. Some information concerning the performances of the detectors which are relevant for the discussion of this new analysis are here recalled together with the features of the neutron detection.

FINUDA was a magnetic spectrometer, immersed in a uniform solenoidal magnetic field of 1 T and optimized for the detection of charged particles, with an angular coverage of $\sim 2\pi$ sr [11]. The outer FINUDA detector, called TOFONE [10,11] was a barrel of 72 plastic $(\text{CH})_n$ scintillator slabs (255 cm long and 10 cm thick), used essentially for trigger and charged particle P.I.d. (by Time Of Flight). It was also used to detect neutrons (and photons) with an

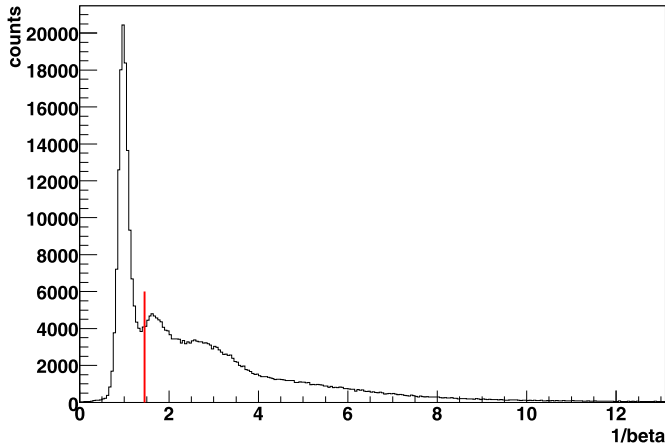


Fig. 2. Distribution of $1/\beta$ for neutral candidates; the line indicates the cut applied in the data analysis.

efficiency of about 10% for neutrons in the kinetic energy range 15–150 MeV.

The inner FINUDA detector was an hodoscope of 12 scintillator thin slabs (TOFINO) arranged around the beam pipe at the (e^+, e^-) interaction point; it was used for trigger purposes and to identify the charged kaons discriminating them from minimum ionizing (Bhabha or beam background) particles. The particle Time-Of-Flight was measured by the (TOFINO–TOFONE) system.

Neutrons and photons are identified looking for events in which TOFONE elements were not connected to the curved trajectories belonging to charged particles.

The β of the neutral particle is evaluated by means of $\beta = (bof/tof)/c$. tof is the measured time between the hit, on the TOFINO, of the K^- from the ϕ decay just before stopping in the target (we neglect the stopping time ≤ 200 ps, since it is much lower than the timing resolution of $\sigma = 780$ ps), and the hit on the TOFONE of the neutral particle. bof is the path length of the neutral particle as determined by the distance between the K^- interaction vertex in the target, measured with a precision of 0.8 mm, and the impact point on the TOFONE slab. The precision on the determination of the impact point on the scintillator slab is $\sigma = 6$ cm.

The analysis of the β values of the neutral candidates allows us to discriminate neutrons from γ 's emitted, for instance, in the π^0 decay. Fig. 2 shows the distribution of $1/\beta$ for selected neutral candidates. The peak centered at $1/\beta = 1$ is due to γ 's and it is followed by the contributions due to neutrons and to γ 's from π^0 decay, which may be delayed if they are produced in the decay of kaons or hyperons.

Applying a cut on the $1/\beta$ value ($1/\beta \geq 1.47$ as indicated by the line in Fig. 2), it is possible to eliminate the γ peak from the neutron candidates detection. As it will be discussed in the following the most effective way to identify neutrons from NMWD is to tag them when they are accompanied by a coincidence proton. In the analysis we selected all the events in which a neutron and a proton are emitted in coincidence with a π^- having a momentum corresponding to the Λ -hypernucleus formation in its ground state or in a low lying excited one (with a π^- momentum resolution of $\sigma \sim 1$ MeV/c), decaying to the ground state by electromagnetic emission.

For the calibration of the neutron energy scale we used the monochromatic neutrons (185 MeV/c) produced in the decay at rest of the Σ^+ coming from the $K_{stop}^- + p \rightarrow \Sigma^+ + \pi^-$ reaction. The experimental peak is centered at 187.6 MeV/c with a $\sigma = 9.4$ MeV/c. By combining the precision on the determination of

the impact point of the neutrons on the scintillator slab and the timing resolution reported before we finally obtain for the overall energy resolution on the neutron $\sim 13\%$ at 10 MeV and $\sim 20\%$ at 100 MeV. A detailed description of the TOFONE performances can be found in [13].

We analyzed neutron spectra coming from NMWD of hypernuclei by using the same procedures adopted for the proton spectra described in [14], i.e., by requiring the coincidence of a π^- from the K^- interaction vertex with a momentum compatible with the formation of the hypernucleus with a bound Λ , but the result was unsuccessful. The neutron spectra were affected by a huge background, due to the contaminations described above, that we could not reduce neither by applying suitable cuts on the experimental spectra nor with the help of simulations. We then considered the neutron spectra obtained by requiring not only the presence of a π^- , but also of a proton in quasi-b.t.b. (back-to-back) correlation with the neutron ($\cos\theta(np) \leq -0.8$). The number of such triple coincidence events was quite low, typically of the order of twenty for each nuclear target, and we could not infer from their distribution reliable conclusions. We added the events from all hypernuclear species, and we compared neutron and proton spectra obtained after the acceptance correction and the subtraction of the background due to the $K(np) \rightarrow \Sigma^- p$ absorption, followed by the in-flight $\Sigma^- \rightarrow \pi^- n$ decay [14].

Fig. 3 (first row) shows the result; the two spectra, 3(a) for protons and 3(b) for neutrons, are quite similar, as expected. The proton coincidence with a quasi-b.t.b. neutron enhances the number of events due to the process (3) with respect to the 2N-induced channels. On the other hand the quasi-b.t.b. requirement reduces the number of events in the low energy region, which are due to the channel (3) and (4) followed by a re-scattering inside the nucleus (FSI); in addition the b.t.b. correlation reduces the number of events from the 2N-induced decay (5), which are expected to exhibit a typical 3-body phase space angular and energy distribution. A confirmation of such expectation was found by requiring a tighter angular correlation ($\cos\theta(np) \leq -0.9$) and the result is reported in Fig. 3(c) for protons and 3(d) for neutrons: the low energy region for both neutron and proton spectra is depleted and this confirms the validity of the analysis method.

Taking into account the efficacy of the method described above, we have analyzed the triple (π^-, n, p) coincidences considering separately each hypernucleus. We showed in [10] that the single proton spectra from NMWD of ${}^5_\Lambda\text{He}$ and the p -shell hypernuclei ${}^7_\Lambda\text{Li}$, ${}^9_\Lambda\text{Be}$, ${}^{11}_\Lambda\text{B}$, ${}^{12}_\Lambda\text{C}$, ${}^{13}_\Lambda\text{C}$, ${}^{15}_\Lambda\text{N}$ and ${}^{16}_\Lambda\text{O}$ had a similar behaviour, i.e., a bump around 80 MeV, due to reaction (3) without FSI, and a rise in the low energy region, increasing with A , due to FSI and to channel (5). A fit to each spectrum beyond 80 MeV by using a Gaussian function with free mean values and sigma allowed us to disentangle the contributions due to process (3), the effect of FSI and process (5) and to determine: $\Gamma_{2N}/\Gamma_p = 0.43 \pm 0.25$ and $\Gamma_{2N}/\Gamma_{\text{NMWD}} = 0.24 \pm 0.10$ [10].

In the analysis of the events due to triple (π^-, n, p) coincidences first of all we fixed for each hypernucleus a proton kinetic energy limit E_p placed at 20 MeV below the mean value μ of the Gaussian found in [10] (see Fig. 1). In order to enhance the contribution of the 2N-induced NMWD we also chose an upper limit for the proton–neutron angular correlation of $\cos\theta(np) = -0.8$.

We classified then the triple coincidence (π^-, n, p) events into four groups, according to the following criteria:

- (i) events with proton kinetic energy E_p larger than the limit and $\cos\theta(np) \leq -0.8$. These events should stem mainly from the process (3) without FSI of the proton, even if a negligible contribution from the reaction (5) is expected. Note that we neglect the process (6) following theoretical arguments

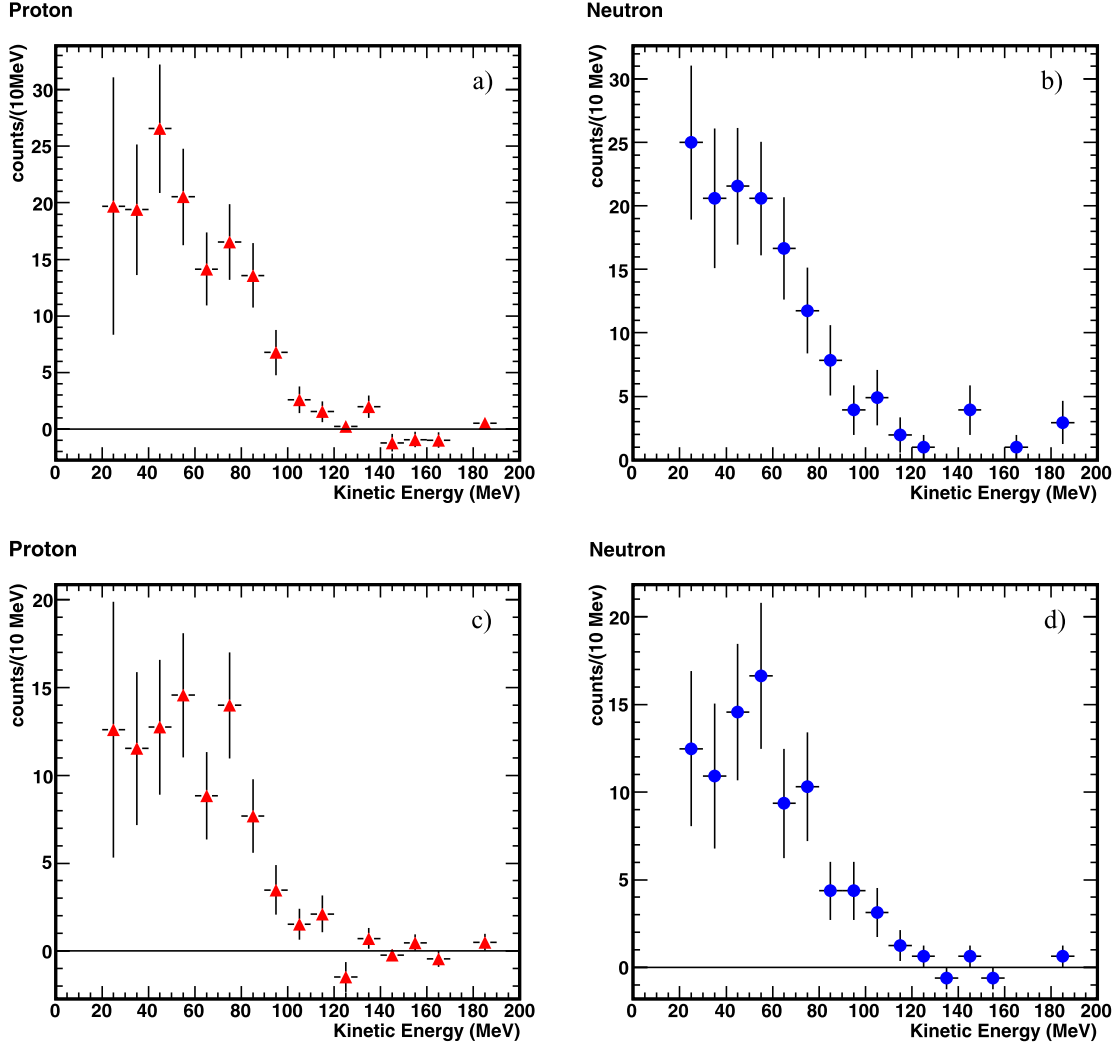


Fig. 3. Upper row: kinetic energy spectra of proton (a) and neutron (b) with a quasi-b.t.b. correlation ($\cos\theta(np) \leq -0.8$) detected in coincidence with a π^- with a momentum compatible with the formation of a Λ hypernucleus; lower row: kinetic energy spectra of proton (c) and neutron (d) with an angular correlation of ($\cos\theta(np) \leq -0.9$) detected in coincidence with a π^- with a momentum compatible with the formation of a Λ hypernucleus.

which indicate that $2N$ -induced NMWD can be assumed to be dominated by the $\Lambda np \rightarrow nnp$ channel. A recent microscopical calculation [15] delivers $\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$;

- (ii) events with E_p larger than the limit and $\cos\theta(np) \geq -0.8$. These events should correspond mainly to the process (3) or (4) followed by a FSI in addition to a small contribution from (5);
- (iii) events with E_p lower than the limit and $\cos\theta(np) \leq -0.8$. These events should correspond mainly to the process (3) with FSI of the proton;
- (iv) events with E_p lower than the limit and $\cos\theta(np) \geq -0.8$. These events should correspond mainly to the process $\Lambda np \rightarrow nnp$ with a not negligible contribution of FSI.

The cuts applied in the selection (iv) produce an underestimation of the population of this group which can be estimated to be 20%. This estimation is based on the assumption of a ≥ 4 -body phase space distribution of $\cos\theta(np)$; for the underestimation due to the cut on E_p the calculation of [16] has been used.

The neutron acceptance for these events was evaluated by taking into account the apparatus geometry, the efficiency of the FINUDA pattern recognition algorithm and the quality cuts applied to the real data. The emission of a neutron from a K^- stopped in

the target was simulated, assigning to the neutron, emitted in coincidence with a proton and a negative pion, a flat momentum distribution from 100 MeV/c to 700 MeV/c. The proton momentum was also simulated with a flat distribution in the same range of the neutron and the π^- momentum was simulated in the range (270–290) MeV/c corresponding to the formation of the Λ hypernuclei. The acceptance function was evaluated target by target in different apparatus sectors and it was found to be flat within 20% in the energy range (10–100) MeV.

3. Experimental results and discussion

We considered the dependence on the mass number A of the ratio R between the events of the selection (iv) and the number of protons with $E_p \geq \mu$. This last number was evaluated by integrating the number of events of the proton spectra above the mean value μ of the Gaussian fit of [10] for each hypernucleus. We have:

$$R \equiv \frac{N_n(E_p \leq (\mu - 20 \text{ MeV}), \cos\theta(np) \geq -0.8)}{N_p(E_p > \mu)} = \frac{0.8N(\Lambda np \rightarrow nnp) + N_n^{\text{FSI}1N} + N_n^{\text{FSI}2N}}{0.5N(\Lambda p \rightarrow np) + N_p^{\text{FSI}1N}} \quad (8)$$

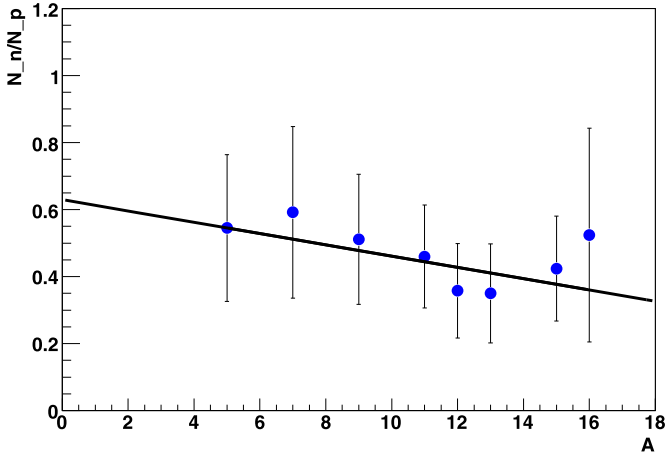


Fig. 4. The ratio $N_n(E_p \leq (\mu - 20 \text{ MeV}), \cos\theta(np) \geq -0.8)/N_p(E_p > \mu)$ as a function of the mass number A .

where $N_n(E_p \leq (\mu - 20 \text{ MeV}), \cos\theta(np) \geq -0.8)$ corresponds to the number of neutrons fulfilling the condition (iv) and that we estimate to be 80% of the total number of neutron coming from the process (5), $N_p(E_p > \mu)$ is the number of protons with an energy higher than the mean value of the fit reported in [10]; $N_n^{\text{FSI}1N}$, $N_p^{\text{FSI}1N}$, $N_n^{\text{FSI}2N}$, $N_p^{\text{FSI}2N}$ are the number of protons or neutrons which suffer the final state interaction effect following the one-(1N) or two-nucleon (2N) induced NMWD. In Fig. 4 the experimental values of this ratio for each hypernucleus are plotted as a function of A .

We then consider a fitting procedure of the data of Fig. 4. By taking as a guidance models of FSI based on the semiclassical nucleon propagation through the residual nucleus (i.e., intranuclear cascade models), one can assume as a first approximation that each weak decay nucleon can interact with only one nucleon of the residual nucleus at a time. Therefore, nucleon FSI effects (i.e., $N_n^{\text{FSI}1N}$, $N_n^{\text{FSI}2N}$ and $N_p^{\text{FSI}1N}$) are assumed to be proportional to the number of nucleons of the residual nucleus, i.e., to A . We thus performed a fit with a function $R(A) = (a' + b'A)/(c + dA)$ and we found $d/c \leq 10^{-3}$; so a simple linear fit $R(A) = (a + bA)$ can be applied. The result of such a fit ($a = 0.63 \pm 0.25$, $b = -0.017 \pm 0.021$ and $\chi^2/\text{ndf} = 0.298/6$) is reported in Fig. 4.

The NMWD (one- or two-body induced) is a short ranged process. In the decay the hyperon can interact with the nearest neighbors nucleons, thus leading to a mechanism of saturation for each one of the one- and two-nucleon induced decay rates for increasing A . By inspecting the experimental data one conclude that the decaying Λ can interact only with s - and p -shell nucleons [17]. In addition, by neglecting shell effects, one- and two-body decay rates should go linearly with A before saturation (i.e., for $A \approx 15$). As a first approximation one can thus take the ratio Γ_{np}/Γ_p as independent of the hypernuclear species, at least for the mass number range of the hypernuclei analyzed in the present work. This approximation is supported by the calculation of Ref. [6]. Moreover, one has:

$$\frac{N(\Lambda np \rightarrow nnp)}{N(\Lambda p \rightarrow np)} = \frac{\Gamma_{np}}{\Gamma_p}, \quad (9)$$

thus Eq. (8) provides:

$$R(A) \equiv \frac{0.8\Gamma_{np}}{0.5\Gamma_p} + bA. \quad (10)$$

Eq. (10) can be solved for Γ_{np}/Γ_p , giving:

$$\frac{\Gamma_{np}}{\Gamma_p} = \frac{[R(A) - bA]}{1.6} = \frac{a}{1.6} = 0.39 \pm 0.16_{\text{stat}}^{+0.04_{\text{sys}}}_{-0.03_{\text{sys}}} \quad (11)$$

where a with its error is taken from the fit.

The systematic errors on Γ_{np}/Γ_p take into account the effect of slight variations in the selection criteria applied on $\cos\theta(np)$ and on the limit of the proton energy E_p ; their value is significantly smaller than the statistical error. In addition, the possible uncertainty on the underestimation of population of group (iv) has been included.

As pointed out in Section 2 recent calculation of [15] delivers $\Gamma_{np} : \Gamma_{pp} : \Gamma_{nn} = 0.83 : 0.12 : 0.04$. Ref. [15] presents an improvement of the first calculation of the 2N-induced decay rates performed within a nuclear matter framework [4], where a phenomenological description of the two-particle two-hole polarization propagator was adopted; the effects of Pauli exchange terms in the two-nucleon stimulated NMWD are also taken into account in [15]. Considering that the total error on Γ_{np}/Γ_p quoted in Eq. (11) is bigger than the contribution of $(\Gamma_{pp} + \Gamma_{nn})$, in the present analysis we can assume $\Gamma_{2N} \sim \Gamma_{np}$ as in [10]. We can determine $\Gamma_{2N}/\Gamma_{\text{NMWD}}$ by adopting the same method employed in [10]; using the experimental value of Γ_n/Γ_p reported in [8] for ${}^5_\Lambda\text{He}$ and ${}^{12}_\Lambda\text{C}$ and our determination of Γ_{np}/Γ_p we obtain:

$$\frac{\Gamma_{2N}}{\Gamma_{\text{NMWD}}} = \frac{\Gamma_{2N}/\Gamma_p}{(\Gamma_n/\Gamma_p) + 1 + (\Gamma_{2N}/\Gamma_p)} = 0.21 \pm 0.07_{\text{stat}}^{+0.03_{\text{sys}}}_{-0.02_{\text{sys}}}. \quad (12)$$

This value supports the latest theoretical predictions [6] ($\Gamma_2/\Gamma_{\text{NMWD}} = 0.26$), the recent experimental results of [9] (0.29 ± 0.13) and the previous FINUDA result [10], but bears a smaller error.

4. Conclusions

We performed an analysis of the 2N-induced NMWD process $\Lambda np \rightarrow nnp$ by analyzing the (π^-, p, n) triple coincidence events from K^- stopped in thin nuclear targets with the FINUDA spectrometer at DAΦNE. The measurement of the π^- momentum allowed the selection of events coming from the decay of p -shell Λ -hypernuclei. By applying appropriate cuts on the energies and angles of the protons and the neutrons we could identify events due mainly to $\Lambda np \rightarrow nnp$ NMWD and determine $\Gamma_{np}/\Gamma_p = 0.39 \pm 0.16_{\text{stat}}^{+0.04_{\text{sys}}}_{-0.03_{\text{sys}}}$. We also extracted $\Gamma_{2N}/\Gamma_{\text{NMWD}} = 0.21 \pm 0.07_{\text{stat}}^{+0.03_{\text{sys}}}_{-0.02_{\text{sys}}}$. We notice that this value agrees well within the errors with two previous estimations based on different methodological approaches. We have then three values reported by different analysis of different experiments leading to the same values, within the errors, unfortunately still quite large. We hope that these limited statistics results will be confirmed by experiments planned at J-PARC.

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