



Determination of non-mesonic weak decay widths of ${}^5_{\Lambda}\text{He}$ and ${}^{11}_{\Lambda}\text{B}$ Hypernuclei



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ABSTRACT

The recent determination of the partial decay widths for the one-proton and the two-nucleon induced Non-Mesonic Weak Decay of Λ -Hypernuclei in the $A = 5$ –16 range permitted to reconstruct the full pattern of decay widths for ${}^5_{\Lambda}\text{He}$ and ${}^{11}_{\Lambda}\text{B}$. A consistency check on ${}^{12}_{\Lambda}\text{C}$ decay widths confirms the validity of the adopted method.

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1. Introduction

Weak Interaction mediates the Λ -Hypernuclei (Hypernuclei in the following) decay to non-strange nuclear systems through different channels (Weak Decays, WD).

The simplest process is the so-called Mesonic Weak Decay (MWD), which is closely related to the two main decay channels into $N\pi$ of the constituent Λ hyperon in free space. The associated decay widths are labeled Γ_{π^-} and Γ_{π^0} and their sum Γ_M . The MWD is the most important decay mode for the s -shell Hypernuclei, it remains quite significant, at the level of ~ 15 –20% of the total decay width, in the case of p -shell Hypernuclei, while it becomes negligible for medium- to high- A Hypernuclei.

The so-called Non-Mesonic Weak Decay (NMWD) channels are instead linked to the occurrence of Weak Interactions among the constituent Λ hyperon and one or more nucleons of the nuclear core of a Hypernucleus. The process $\Lambda N \rightarrow NN$ is the simplest one: usually it is referred to as proton-stimulated decay, in the case of the $\Lambda p \rightarrow np$ elementary reaction, with a decay width Γ_p , or neutron-stimulated decay in the case of the $\Lambda n \rightarrow nn$ interaction, with a corresponding Γ_n . The importance of the one-nucleon (1N) induced NMWD was immediately recognized since the early days of Hypernuclear Physics [1] as a unique tool to achieve quantitative information on the $\Lambda N \rightarrow NN$ Weak Interaction, very hardly accessible in free space. Such a statement still holds today, despite more than six decades of remarkable progress in the technology of accel-

erators, of particle detectors and of computing devices. Quite later, a further NMWD channel was predicted, associated to the elementary $\Lambda(NN) \rightarrow n(NN)$ interaction on a pair of correlated nucleons in the nuclear core of the Hypernucleus ($2N$ induced) [2], with a corresponding decay width Γ_{2N} . Γ_{2N} may be further split into the three branches corresponding to the three projections of the total Isospin of the NN pair. However the dominant configuration is the one corresponding to the $I_3 = 0$ component (np) predicted to account for $\sim 83\%$ of the total Γ_{2N} width [3]. Γ_{NM} is then the sum of Γ_p , Γ_n and Γ_{2N} . The NMWD channels are the dominant ones in all but the s -shell Hypernuclei.

We do not report here the specific decay schemes for all the above five (or seven) channels, which are straightforward. Actually, a lot of different configurations for the residual nuclear system produced in the different decay processes are possible (a single nucleus in the ground or low-lying excited state or two or more fragments, ...). The total decay width Γ_T for a given Hypernucleus is finally given by:

$$\Gamma_T = \Gamma_M + \Gamma_{NM} = \Gamma_{\pi^-} + \Gamma_{\pi^0} + \Gamma_p + \Gamma_n + \Gamma_{2N}. \quad (1)$$

In order to compare data about different Hypernuclei, partial Γ 's are usually given in units of Γ_{Λ} , the total decay width of the free Λ ; equation (1) is then rewritten as:

$$\frac{\Gamma_T}{\Gamma_{\Lambda}} = \frac{\Gamma_M + \Gamma_{NM}}{\Gamma_{\Lambda}} = \frac{\Gamma_{\pi^-}}{\Gamma_{\Lambda}} + \frac{\Gamma_{\pi^0}}{\Gamma_{\Lambda}} + \frac{\Gamma_p}{\Gamma_{\Lambda}} + \frac{\Gamma_n}{\Gamma_{\Lambda}} + \frac{\Gamma_{2N}}{\Gamma_{\Lambda}}. \quad (2)$$

It appears that in principle it is necessary to measure six quantities to fully describe the decay features of a Hypernucleus (the five

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Γ s and its lifetime). Several experiments reported partial measurements of the different WD widths. A recent review on Hypernuclei Weak Decays may be found in Ref. [4].

Moreover, in addition to the experimental hardness intrinsic to the NMWD observation, one has to face the effects of intranuclear cascade processes (Final State Interaction, FSI), already quite significant for light hypernuclear systems like the ${}^5_{\Lambda}\text{He}$ Hypernucleus. A systematic summary of the measurements of all the Γ s for ${}^{12}_{\Lambda}\text{C}$ performed at the KEK PS is reported in Ref. [5]: it is the only complete determination carried out so far. The main breakthroughs with respect to previous experiments were the determination of $\Gamma_{2N}/\Gamma_{\Lambda}$, which was found to be equal to (0.27 ± 0.13) , and an updated estimation of the FSI effects. Γ_{2N} was determined by the FINUDA Collaboration for the Hypernuclei in the $A = 5\text{--}16$ range thanks to a study of the proton spectra and of the neutron–proton coincidence spectra in suitable kinematical configurations, as described in Refs. [6–8]. A constant value of

$$\Gamma_{2N}/\Gamma_p = 0.36 \pm 0.14_{\text{stat}-0.04_{\text{sys}}}^{+0.05_{\text{sys}}} \quad (3)$$

was obtained, which will be used in the following. From (3) a value of $\Gamma_{2N}/\Gamma_{NM} = (0.20 \pm 0.08_{\text{stat}-0.03_{\text{sys}}}^{+0.04_{\text{sys}}})$ was calculated. Moreover, in the most recent paper [8], a determination of $\Gamma_p/\Gamma_{\Lambda}$ for eight Hypernuclei was given as well. Then, the availability of $\Gamma_p/\Gamma_{\Lambda}$ and $\Gamma_{2N}/\Gamma_{\Lambda}$ in the $A = 5\text{--}16$ range offers the possibility of constructing full WD patterns for some Hypernuclei in the above mentioned A range, by merging the information on $\Gamma_T/\Gamma_{\Lambda}$, $\Gamma_{\pi^-}/\Gamma_{\Lambda}$ and $\Gamma_{\pi^0}/\Gamma_{\Lambda}$ provided by other experiments. The processes with neutral particles in the final state are obviously the hardest to be measured. However, good quality data samples exist on $\Gamma_{\pi^0}/\Gamma_{\Lambda}$ for ${}^5_{\Lambda}\text{He}$ and ${}^{11}_{\Lambda}\text{B}$. Then, by exploiting equation (2) it was possible to derive by difference $\Gamma_n/\Gamma_{\Lambda}$, even though with large error, and finally to obtain the full pattern of the WD widths for ${}^5_{\Lambda}\text{He}$ and ${}^{11}_{\Lambda}\text{B}$.

2. The NMWD widths of ${}^5_{\Lambda}\text{He}$

The first experiment which produced a full set of WD widths for ${}^5_{\Lambda}\text{He}$ and ${}^{12}_{\Lambda}\text{C}$ and which pioneered all the following efforts was performed at the BNL AGS [9]. A value for $\Gamma_n/\Gamma_{\Lambda}$ of (0.20 ± 0.11) was deduced from (7.7 ± 3.3) neutron events, background subtracted. A possible contribution of the $2N$ induced decay was not taken into account since at that time it was not even anticipated theoretically. The value $\Gamma_n/\Gamma_p = (0.93 \pm 0.55)$ which was finally published is then unavoidably biased by this omission. Both the $\Gamma_n/\Gamma_{\Lambda}$ and $\Gamma_p/\Gamma_{\Lambda} = (0.21 \pm 0.07)$ values were corrected for FSI. Further measurements of $\Gamma_{\pi^-}/\Gamma_{\Lambda}$, of $\Gamma_{\pi^0}/\Gamma_{\Lambda}$ and of $\Gamma_T/\Gamma_{\Lambda}$ were reported in Refs. [10,11], in Ref. [12] and in Ref. [10], respectively. A very recent determination of $\Gamma_p/\Gamma_{\Lambda}$ was published in Ref. [8]; on the basis of such a result and by exploiting equation (3) an evaluation of $\Gamma_{2N}/\Gamma_{\Lambda}$ was obtained as well.

A compilation of the above WD widths values is reported in the first four rows of the second column of Table 1. When more than one measurement is available in the literature, we quoted the weighted average (w.a.). The $\Gamma_n/\Gamma_{\Lambda}$ value was calculated by difference according to equation (2). Consequently, it is affected by a quite large error, which characterizes also the Γ_n/Γ_p ratio, shown in the seventh row of Table 1. It turns out to be consistent with the value $\Gamma_n/\Gamma_p = (0.45 \pm 0.11_{\text{stat.}} \pm 0.03_{\text{sys.}})$ obtained in the direct measurement in which the neutron and the proton were detected in tight back-to-back topology and by applying further constraints on the nucleon energy which permitted the selection of events for which the FSI effect were not so important [13].

Table 1

WD widths for ${}^5_{\Lambda}\text{He}$, ${}^{11}_{\Lambda}\text{B}$ and ${}^{12}_{\Lambda}\text{C}$ Hypernuclei. The existing experimental data for $\Gamma_T/\Gamma_{\Lambda}$, $\Gamma_{\pi^-}/\Gamma_{\Lambda}$, $\Gamma_{\pi^0}/\Gamma_{\Lambda}$ and $\Gamma_p/\Gamma_{\Lambda}$ have been integrated with the determination of $\Gamma_{2N}/\Gamma_{\Lambda}$, $\Gamma_n/\Gamma_{\Lambda}$ and Γ_n/Γ_p . This latter result is compared with theoretical predictions from Ref. [20], shown in the last row. The values obtained for ${}^{12}_{\Lambda}\text{C}$ are compared with measurements described in Ref. [5], listed in the last column.

	${}^5_{\Lambda}\text{He}$	${}^{11}_{\Lambda}\text{B}$	${}^{12}_{\Lambda}\text{C}$	${}^{12}_{\Lambda}\text{C}$ [5]
$\Gamma_T/\Gamma_{\Lambda}$	0.962 ± 0.034 [9,10]	1.274 ± 0.072 [18,19]	1.241 ± 0.041 [5]	1.241 ± 0.041
$\Gamma_{\pi^-}/\Gamma_{\Lambda}$	0.342 ± 0.015 [9–11]	0.228 ± 0.027 [11,14–16]	0.120 ± 0.014 [5,9,15]	0.123 ± 0.015
$\Gamma_{\pi^0}/\Gamma_{\Lambda}$	0.201 ± 0.011 [12]	0.192 ± 0.056 [17]	0.1656 ± 0.0080 [12,17]	0.165 ± 0.008
$\Gamma_p/\Gamma_{\Lambda}$	0.217 ± 0.041 [8,9]	0.47 ± 0.11 [8]	0.493 ± 0.088 [5,8]	0.45 ± 0.10
$\Gamma_{2N}/\Gamma_{\Lambda}$	0.078 ± 0.034 [this work]	0.169 ± 0.077 [this work]	0.178 ± 0.076 [this work]	0.27 ± 0.13
$\Gamma_n/\Gamma_{\Lambda}$	0.125 ± 0.066 [this work]	0.21 ± 0.16 [this work]	0.28 ± 0.12 [this work]	0.23 ± 0.08
Γ_n/Γ_p	0.58 ± 0.32 [this work]	0.46 ± 0.37 [this work]	0.58 ± 0.27 [this work]	0.51 ± 0.14
Γ_n/Γ_p [20]	0.508	0.502	0.418	–

3. The NMWD widths of ${}^{11}_{\Lambda}\text{B}$

There is a considerable amount of measurements of partial WD for this Hypernucleus, due to the circumstances that it is produced together with ${}^{12}_{\Lambda}\text{C}$ that is the most studied Hypernuclear system. As a matter of fact, in all Hypernuclear mass spectra obtained with (K^-, π^-) and (π^+, K^+) production reaction on a ${}^{12}\text{C}$ target two prominent peaks appear, one corresponding to the formation of the ground state of ${}^{12}_{\Lambda}\text{C}$, described as the particle-hole shell-model configuration $(s(\Lambda), p^{-1}(n))$, the other, separated by ~ 11 MeV in excitation energy, corresponding to the $(p(\Lambda), p^{-1}(n))$ configuration and decaying via Strong Interaction to ${}^{11}_{\Lambda}\text{B}$ plus a low-energy proton (undetected). Measurements of $\Gamma_{\pi^-}/\Gamma_{\Lambda}$, of $\Gamma_{\pi^0}/\Gamma_{\Lambda}$ and of $\Gamma_T/\Gamma_{\Lambda}$ can be found in Refs. [11,14–16], in Ref. [17] and in Refs. [18,19], respectively. Values for $\Gamma_p/\Gamma_{\Lambda}$ were reported in Ref. [15] and, more recently, in Ref. [8]. As far as the result described in Ref. [15] is concerned, it is not clear whether the value for $\Gamma_p/\Gamma_{\Lambda}$ was corrected for FSI effect, which can amount up to 100% as shown in Ref. [8]. Then, we did not consider such a value homogeneous with the one reported in Ref. [8] and we did not use it to evaluate a w.a. for $\Gamma_p/\Gamma_{\Lambda}$. By entering the value from Ref. [8] in the formula (3), $\Gamma_{2N}/\Gamma_{\Lambda}$ was determined along with $\Gamma_n/\Gamma_{\Lambda}$ and Γ_n/Γ_p . All these values are reported from the fifth to the seventh row of the third column of Table 1.

4. The consistency check from ${}^{12}_{\Lambda}\text{C}$

To have a consistency check of the above described procedure adopted for ${}^5_{\Lambda}\text{He}$ and ${}^{11}_{\Lambda}\text{B}$, we calculated the NMWD widths of ${}^{12}_{\Lambda}\text{C}$ by using the same method and we compared them with the series of results from Ref. [5], listed in the last column of Table 1. Measurements of $\Gamma_{\pi^-}/\Gamma_{\Lambda}$ and of $\Gamma_{\pi^0}/\Gamma_{\Lambda}$ were reported in Refs. [5, 9,15] and in Refs. [12,17], respectively. For $\Gamma_T/\Gamma_{\Lambda}$ we took into account the last, precise value from Ref. [5]. For $\Gamma_p/\Gamma_{\Lambda}$ we considered the values from Refs. [5,8] only and we excluded the one from Ref. [15] for the same reasons explained above (see Section 3). This way, we obtained the values for $\Gamma_{2N}/\Gamma_{\Lambda}$, Γ_n/Γ_p and Γ_n/Γ_p , reported from the fifth to the seventh row of the fourth column of Table 1. An overall agreement within the errors between the present determination and the previous measurement is evident

and it provides arguments supporting the validity of the method adopted for ${}^5_{\Lambda}\text{He}$ and ${}^{11}_{\Lambda}\text{B}$.

5. Conclusions

In conclusion, we have presented for the first time the full set of WD widths for ${}^5_{\Lambda}\text{He}$ and ${}^{11}_{\Lambda}\text{B}$ Hypernuclei. The values for $\Gamma_n/\Gamma_{\Lambda}$, determined by subtracting the partial widths $\Gamma_M/\Gamma_{\Lambda}$, $\Gamma_p/\Gamma_{\Lambda}$ and $\Gamma_{2N}/\Gamma_{\Lambda}$ from $\Gamma_T/\Gamma_{\Lambda}$, are affected by large errors and consequently also the ones for the Γ_n/Γ_p ratio. They are compatible with the outcome of accurate theoretical calculations [20] reported in the last row of Table 1, which predicted nuclear structure effects as large as 10% in 1N induced NMWD of p -shell Hypernuclei. Strong nuclear structure effects were expected (and they were actually observed [11]) for MWD and at a much lower extent for 1N induced NMWD, due to the damping caused by the larger momentum of the final state particles (~ 400 MeV/ c instead of ~ 100 MeV/ c). It could be interesting to verify these predictions by applying the method described in this Letter to several p -shell Hypernuclei to be observed in a dedicated experiment aiming to measure all the values of the WD widths with errors of the order of 5%. Such a set of results could be well exploited to derive

the physical quantities describing the four-baryon, weak interaction $\Lambda N \rightarrow NN$, not accessible in free space.

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