Nucleon–Nucleon Coincidence Spectra in the Non–Mesonic Weak Decay of Λ–Hypernuclei and the Γ_n/Γ_p Puzzle

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The main open problem in the physics of Λ-hypernuclei is the lack of a sound theoretical interpretation of the large experimental values of the ratio Γ_n/Γ_p, between the neutron- and proton-induced non-mesonic decay widths, Γ(Λn → nn) and Γ(Λp → np), of Λ-hypernuclei is missing [1,2]. The calculations underestimate the central data for all considered hypernuclei, although the large experimental error bars do not allow one to reach any definite conclusion. Moreover, in the experiments performed until now it has not been possible to distinguish between nucleons produced by the one-body induced and the (non–negligible) two–body induced decay mechanism, ΛNN → nNN. Because of its strong tensor component, the one–pion–exchange (OPE) model with the ΔI = 1/2 isospin rule supplies very small ratios, typically in the interval 0.05 ÷ 0.20. On the contrary, the OPE description can reproduce the total non–mesonic decay rates observed for light and medium hypernuclei. Other interaction mechanisms beyond OPE might then be responsible for the overestimation of Γ_p and the underestimation of Γ_n. Those which have been studied extensively in the literature are the following ones: 1) the inclusion in the ΔN → nN transition potential of mesons heavier than the pion (also including the exchange of correlated or uncorrelated two–pions) [3–7]; 2) the inclusion of interaction terms that explicitly violate the ΔI = 1/2 rule [1,8,9]; 3) the inclusion of the two–body induced decay mechanism [10–12] and 4) the description of the short range ΔN → nN transition in terms of quark degrees of freedom [13,14], which automatically introduces ΔI = 3/2 contributions.

Recent progress has been made on the subject. (1) On the one hand, a few calculations [5–7,13] with ΔN → nN transition potentials including heavy–meson–exchange and/or direct quark contributions obtained ratios more in agreement with data, without providing, nevertheless, a satisfactory explanation of the puzzle. In particular, these calculations found a reduction of the proton–induced decay width due to the opposite sign of the tensor component of Κ–exchange with respect to the one for π–exchange. Moreover, the parity violating ΛN(3S1) → nN(3P1) transition, which contributes to both the n– and p–induced processes, is considerably enhanced by Κ–exchange and direct quark mechanisms and tends to increase Γ_n/Γ_p [6,13].

(2) On the other hand, an error in the computer program employed in Ref. [15] to evaluate the single nucleon energy spectra from non–mesonic decay has been detected [16]. It consisted in the underestimation, by a factor ten, of the nucleon–nucleon collision probabilities. The correction of such an error leads to quite different spectral shapes and allows one to extract smaller values of Γ_n/Γ_p (which is a free parameter in the polarization propagator model of Refs. [15,16]) when a comparison with old experimental data for 12C [17] is done.

In the light of these recent developments and of new experiments [18–20], it is important to develop different theoretical approaches and strategies for the determination of the Γ_n/Γ_p ratio. In this Letter we present a finite nucleus calculation of the nucleon–nucleon coincidence distributions in the non–mesonic weak decay of 3He and 12C hypernuclei. The work is motivated by the fact that, unlike the single nucleon spectra, correlation observables permit a cleaner and more direct extraction of Γ_n/Γ_p from data [1]. An experiment performed very recently at KEK [18] has actually measured the angular and energy correlations that we discuss in this paper. Some prelimi-
nary results of the experiment can already be compared with our calculations.

The one–meson–exchange (OME) weak transition potential we employ to describe the one–nucleon stimulated decays contains the exchange of $\rho$, $K$, $K^*$, $\omega$ and $\eta$ mesons in addition to the pion [6]. The final state interactions acting between the two primary nucleons are taken into account by using a scattering $NN$ wave function from the Lippmann–Schwinger ($T$–matrix) equation obtained with the NSC97f potential [21]. The OME decay rates predicted by this model are the following ones [6]: $\Gamma_1 = \Gamma_{NN} + \Gamma_p = 0.32$, $\Gamma_{NN}/\Gamma_p = 0.46$ for $\Lambda^5$He and $\Gamma_1 = 0.55$, $\Gamma_{NN}/\Gamma_p = 0.34$ for $\Lambda^5$C.

The distributions of primary nucleons emitted in two–nucleon induced decays and the ratio $\Gamma_2/\Gamma_1$ has been determined by the polarization propagator method in local density approximation of Ref. [11]: $\Gamma_2/\Gamma_1 = 0.20$ for $\Lambda^5$He and $\Gamma_2/\Gamma_1 = 0.25$ for $\Lambda^5$C [22].

In their way out of the nucleus, the primary nucleons, due to collisions with other nucleons, continuously change energy, direction and charge. As a consequence, secondary nucleons are also emitted. We simulate the nucleon propagation inside the residual nucleus with the Monte Carlo code of Ref. [16].

In Fig. 1 we show the kinetic energy correlation of $np$ coincidence pairs emitted in the non–mesonic decay of $\Lambda^5$He. The spectra are normalized per non–mesonic weak decay. To facilitate a comparison with experiments, whose kinetic energy threshold for proton (neutron) detection is typically of about 30 (10) MeV, and to avoid a possible non–realistic behaviour of the intranuclear cascade simulation for low nucleon energies, in all the figures of the paper we required $T_n$, $T_p \geq 30$ MeV. A narrow peak is predicted close to the $Q$–value (153 MeV) expected for the proton–induced three–body process $\Lambda^5$He $\rightarrow^3$ H $\times n + p$: it is mainly originated by the back–to–back kinematics (cos $\theta_{np} < -0.8$). A broad peak, predominantly due to $\Lambda p \rightarrow np$ or $\Lambda n \rightarrow nn$ weak transitions followed by the emission of secondary (less energetic) nucleons, has been found around 140 MeV for cos $\theta_{np} > -0.8$. The kinetic energy correlation for $\Lambda^5$He $nn$ pairs (Fig. 2) shows essentially the same structure of the $np$ distribution just discussed.

In Fig. 3, which corresponds to the energy correlation of $\Lambda^5$C $nn$ pairs, the narrow peak appearing at $T_n + T_p \approx 155$ MeV again gets the dominant contribution from back–to–back coincidences. The relevance of the nucleon final state interactions (FSI) in $\Lambda^5$C relative to $\Lambda^5$He can be seen from the second, broader peak appearing in the region around 110 MeV for $\Lambda^5$C and 140 MeV for $\Lambda^5$He. This peak is in fact more pronounced for the heavier hypernucleus. Another consequence of the different FSI effects in $\Lambda^5$He and $\Lambda^5$C is the different magnitude of the tail of the back–to–back distribution at low energies.

Figs. 4 and 5 show the opening angle correlations of $nn$, $np$ and $pp$ pairs emitted in the decay of $\Lambda^5$He and $\Lambda^5$C, respectively. Comparing both figures for $nn$ and $np$ coincidences, one sees that the back–to–back peaks are more pronounced for $\Lambda^5$He (less sensitive to FSI than $\Lambda^5$C) than for $\Lambda^5$C, while the (almost uniform) tail of these distributions (feasted by FSI) is more significant in $\Lambda^5$C than in $\Lambda^5$He. Since at least one proton of any $pp$ coincidence is a secondary particle, the $pp$ spectra are quite uniform: actually, due to the relevance of the back–to–back kinematics in the weak decay, these distributions slowly decrease as cos $\theta_{pp}$ increases. Again as a consequence of FSI, the number of $pp$ pairs is considerably larger in $\Lambda^5$C than in $\Lambda^5$He.

The ratio $\Gamma_n/\Gamma_p$ is defined as the ratio between the number of primary weak decay $nn$ and $np$ pairs, $N_{nn}^{wd}$ and $N_{np}^{wd}$. However, due to nucleon FSI, one expects the inequality:

$$\frac{\Gamma_n}{\Gamma_p} = \frac{N_{nn}^{wd}}{N_{np}^{wd}} \neq \frac{N_{nn}}{N_{np}} = f[\Delta\theta_{12}, \Delta(T_1 + T_2)]$$

(1)

to be valid in a situation, such as the experimental one, in which particular intervals of variability of pair opening angle, $\Delta\theta_{12}$, and sum energy, $\Delta(T_1 + T_2)$, are employed in the determination of $N_{nn}$ and $N_{np}$. Actually, as one can deduce from Figs. 1–5, not only $N_{nn}$ and $N_{np}$ but also the ratio $N_{nn}/N_{np}$ depends on $\Delta\theta_{12}$ and $\Delta(T_1 + T_2)$. The numbers of nucleon pairs $N_{nn}$, $N_{np}$ and $N_{pp}$ discussed up to now are related to the corresponding quantities for the one–nucleon ($N_{NN}^{1B}$) and two–nucleon ($N_{NN}^{2B}$) induced processes [the former (latter) being normalized per one–body (two–body) stimulated non–mesonic weak decay] via the following equation:

$$N_{NN} = \frac{N_{NN}^{1B} \Gamma_1 + N_{NN}^{2B} \Gamma_2}{\Gamma_1 + \Gamma_2}.$$  

(2)

Table I shows the dependence of $N_{nn}$, $N_{np}$ and $N_{nn}/N_{np}$ on $\Delta\theta_{12}$ and $\Delta(T_1 + T_2)$ for $\Lambda^5$C. For comparison, the same quantities for the primary weak decay nucleons are listed as well. Without any restriction on $\theta_{NN}$ and the nucleon energies, one notes a great increase (by about one order of magnitude) of both the $nn$ and $np$ numbers when the effect of the FSI is taken into account. Again because of FSI, the use of an energy threshold $T^3_{NN}$ of 30 MeV supplies $N_{nn}$ and $N_{np}$ values considerably reduced with respect to the ones obtained at $T^3_{NN} = 0$ MeV. On the contrary, the ratio between the number of $nn$ and $np$ pairs is much less sensitive to FSI effects.
In Table II (III), the ratio $N_{nn}/N_{np}$ for $^5\Lambda$He ($^{12}\Lambda$C) is given for different combinations of opening angle interval and nucleon energy threshold. In parentheses we also report the predictions obtained when the two–nucleon induced decay channel is neglected. The results of the figures and tables presented in this work are in a form that permits a direct comparison with KEK–E462 data [18], which are now under analysis. The first preliminary results of KEK–E462 are quoted in Table II. We note that while the central values of the data are more in agreement with the calculation that neglects the effect of the two–body induced decay mechanism, the complete results are compatible with the upper limits of the same data. This could indicate an almost negligible effect of the $\Lambda np \rightarrow nnp$ process and/or a $\Gamma_n/\Gamma_p$ ratio slightly lower than the one (0.46) predicted by our OME model for $^5\Lambda$He. To clarify this point, on the one hand one has to wait for the final results of KEK–E462. On the other
hand, our calculations show that three–nucleon coincidences are required to disentangle the effects of one– and two–body stimulated decay channels from observed decay events. The simplistic picture that the back–to–back kinematics is able to select one–nucleon induced processes is in fact far from being realistic.

In conclusion, our OME weak interaction model supplemented by FSI through an intranuclear cascade simulation provides two–nucleon coincidence observables which reproduce the preliminary KEK–E462 results for \( \Lambda^4 \)He. This allows us to conclude that \( \Gamma_n/\Gamma_p \) for \( \Lambda^4 \)He should be close to 0.46. Although further (theoretical and experimental) confirmation is needed, in this paper we think we have proved how the study of nucleon coincidence observables can offer a promising possibility to solve the longstanding puzzle on the \( \Gamma_n/\Gamma_p \) ratio.

In a forthcoming (long) paper \[23\] we shall discuss the nucleon correlation observables for the (one– and two–nucleon stimulated) non–mesonic decay of \( \Lambda^4 \)He and \( \Lambda^3 \)C in a systematic way. Single nucleon spectra will be further subject of this work. In addition, one should treat the case of \( 1^4 \)H, which is of extreme importance in order to test the validity of the \( \Delta \)I = 1/2 isospin rule in the \( \Lambda N \rightarrow nN \) weak transition \[1,9,20\], another key point for the solution of the \( \Gamma_n/\Gamma_p \) puzzle.

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**TABLE I.** Results for \( N_{nn}, N_{np} \) and \( N_{nn}/N_{np} \) corresponding to the non–mesonic decay of \( \Lambda^3 \)C. A null (30 MeV for the numbers in parentheses) nucleon energy threshold and two different opening angle regions are considered.

| \( \cos \theta_{NN} \) | all \( \theta_{NN} \) |
|-----------------|-----------------|
| \( N_{nn}^{wd} \) | 0.20 (0.19) | 0.25 (0.24) |
| \( N_{np}^{wd} \) | 0.57 (0.56) | 0.75 (0.72) |
| \( N_{nn}^{wd}/N_{np}^{wd} \equiv \Gamma_n/\Gamma_p \) | 0.34 (0.34) | 0.34 (0.34) |
| \( N_{nn} \) | 0.44 (0.11) | 3.15 (0.33) |
| \( N_{np} \) | 1.05 (0.26) | 8.40 (0.87) |
| \( N_{nn}/N_{np} \) | 0.42 (0.43) | 0.38 (0.39) |

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**TABLE II.** Predictions of \( N_{nn}/N_{np} \) for \( \Lambda^4 \)He corresponding to different nucleon thresholds \( T_N^\lambda \) and pair opening angles. The numbers in parentheses correspond to calculations with \( \Gamma_2 = 0 \) in Eq. (2). The (preliminary) data are from KEK–E462 [18].

| \( T_N^\lambda \) (MeV) | \( \cos \theta_{NN} \) |
|-----------------|-----------------|
| \( \leq -0.8 \) | \( \leq -0.6 \) | \( \leq -0.4 \) | all \( \theta_{NN} \) |
| 30 | 0.61 (0.52) | 0.61 (0.51) | 0.60 (0.50) | 0.54 (0.45) |
| | 0.52 ± 0.11 | 0.50 ± 0.10 | 0.51 ± 0.10 |
| 50 | 0.63 (0.52) | 0.61 (0.51) | 0.60 (0.51) | 0.56 (0.46) |

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**TABLE III.** Same as in Table II for \( \Lambda^3 \)C.

| \( T_N^\lambda \) (MeV) | \( \cos \theta_{NN} \) |
|-----------------|-----------------|
| \( \leq -0.8 \) | \( \leq -0.6 \) | \( \leq -0.4 \) | all \( \theta_{NN} \) |
| 30 | 0.43 (0.37) | 0.43 (0.37) | 0.43 (0.37) | 0.39 (0.35) |
| 50 | 0.41 (0.35) | 0.40 (0.35) | 0.40 (0.35) | 0.38 (0.34) |