Non–Mesonic Weak Decay of Λ–hypernuclei: a new determination of the $\Gamma_n/\Gamma_p$ ratio

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Theoretical descriptions of the non–mesonic weak decay of Λ–hypernuclei are unable to reproduce the experimental values of the ratio $\Gamma_n/\Gamma_p \equiv \Gamma(\Lambda n \to nn)/\Gamma(\Lambda p \to np)$. In this contribution we discuss a new approach to this problem. We have incorporated a one–meson–exchange model for the $\Lambda N \to nN$ transition in finite nuclei in an intranuclear cascade code for the calculation of double–coincidence nucleon distributions corresponding to the non–mesonic decay of $^5\Lambda$He and $^{12}\Lambda$C. The two–nucleon induced decay mechanism, $\Lambda np \to nnp$, has been taken into account within a local density approximation scheme using a one–pion–exchange model supplemented by short range correlations. A weak decay model independent analysis of preliminary KEK coincidence data for $^5\Lambda$He allows us to extract $\Gamma_n/\Gamma_p = 0.39 \pm 0.11$ when the two–nucleon induced channel is neglected (i.e., $\Gamma_2 = 0$) and $\Gamma_n/\Gamma_p = 0.26 \pm 0.11$ when $\Gamma_2/\Gamma_1 = 0.2$.

1. INTRODUCTION

An old challenge of hypernuclear studies has been to secure the “elusive” theoretical explanation of the large experimental values ($\simeq 1$) of the ratio $\Gamma_n/\Gamma_p$, between the neutron– and proton–induced non–mesonic decay rates, $\Gamma_n \equiv \Gamma(\Lambda n \to nn)$ and $\Gamma_p \equiv \Gamma(\Lambda p \to np)$ [1, 2].

Because of its strong tensor component, the one–pion–exchange (OPE) model supplies very small $\Gamma_n/\Gamma_p$ ratios, typically in the interval $0.05 \div 0.20$ for $s$– and $p$–shell hypernuclei. On the contrary, the OPE description can reproduce the total non–mesonic decay rates observed for these systems. Other interaction mechanisms are then expected to correct for the overestimation of $\Gamma_p$ and the underestimation of $\Gamma_n$ characteristic of the OPE. Those which have been studied extensively in the literature are the following ones: i) the inclusion in the $\Lambda N \to nN$ transition potential of mesons heavier than the pion (also including the exchange of correlated or uncorrelated two–pions) [3–6]; ii) the inclusion of interaction terms that explicitly violate the $\Delta I = 1/2$ rule [1, 7, 8]; iii) the inclusion of the two–body induced decay mechanism [9–12] and iv) the description of the short range

*Work partly supported by EURIDICE HPRN–CT–2002–00311, DGICYT BFM2002–01868, Generalitat de Catalunya SGR2001–64 and INFN.
ΛN → nN transition in terms of quark degrees of freedom [13], which automatically introduces $\Delta I = 3/2$ contributions.

Some progress in the theory of non–mesonic decay has been experienced in the last years. A few calculations [4–6, 13] with $\Lambda N \rightarrow nN$ transition potentials including heavy–meson–exchange and/or direct quark contributions obtained ratios more in agreement with data, without providing, nevertheless, an explanation of the origin of the puzzle [1]. Very recently, the $\Lambda N \rightarrow nN$ interaction has been studied within an effective field theory framework [14] with a weak decay model consisting of OPE, one–kaon–exchange and $|\Delta S| = 1$ four–fermion contact terms.

In the light of the experiments under way and/or planned at KEK [15], FINUDA [16] and BNL [17], it is important to develop different theoretical approaches and strategies for the determination of $\Gamma_n/\Gamma_p$ from data. In this contribution we discuss an evaluation of nucleon–nucleon coincidence distributions in the non–mesonic weak decay of $^5\Lambda$He and $^{12}\Lambda$C [18]. This work is motivated by the fact that, in principle, correlation observables permit a cleaner extraction of $\Gamma_n/\Gamma_p$ from data than single–nucleon observables. This is due to the elimination of interference terms between $n$– and $p$–induced decays [1], which are unavoidable in experimental data and cannot be taken into account by the Monte Carlo methods usually employed to simulate the nucleon propagation through the residual nucleus. For a detailed discussion of this issue see Ref. [18].

The calculations are performed by combining a one–meson–exchange (OME) model describing one–nucleon induced weak decays in finite nuclei with an intranuclear cascade code taking into account the nucleon final state interactions. The two–nucleon induced channel is also taken into account, treating the nuclear finite size effects by means of a local density approximation scheme.

We also perform a weak interaction model independent analysis to extract an estimate for $\Gamma_n/\Gamma_p$ using preliminary results from KEK [15, 19] on two–nucleon angular and energy correlations. The resulting $\Gamma_n/\Gamma_p$ values for $^5\Lambda$He turn out to be substantially smaller than those obtained from single nucleon distributions analyses [20, 21] and fall within the predictions of recent theoretical studies [5, 6, 13].

The work is organized as follows. In Sec. 2 we give an outline of the models employed to describe the non–mesonic weak decay and we discuss the main features of the intranuclear cascade simulation accounting for the nucleon propagation inside the residual nucleus. A selection of our results is discussed in Sec. 3 and the conclusions are given in Sec. 4.

2. MODELS

2.1. Weak decay

The one–nucleon induced non–mesonic decay rates and the distributions of the nucleons produced in these processes are obtained with the OME model of Refs. [3, 5]. The OME weak transition potential contains the exchange of $\rho$, $K$, $K^*$, $\omega$ and $\eta$ mesons in addition to the pion. The strong couplings and strong final state interactions acting between the weak decay nucleons are taken into account by using a scattering $nN$ wave function from the Lippmann–Schwinger ($T$–matrix) equation obtained with NSC97 (versions “a” and “f”) potentials [22]. The corresponding decay rates for $^5\Lambda$He and $^{12}\Lambda$C are listed in Table 1 (OMEa and OMEf) together with the OPE predictions.
Table 1
Weak decay rates (in units of the free \(\Lambda\) decay width) predicted by Ref. [5] for \(^5\Lambda\)He and \(^{12}\Lambda\)C.

|       | \(\Gamma_n + \Gamma_p\) | \(\Gamma_n/\Gamma_p\) |
|-------|-------------------------|-------------------------|
| OPE   | OMEa                    | OMEf                    |
| \(^5\Lambda\)He | 0.43 0.43 0.32           | 0.09 0.34 0.46          |
| \(^{12}\Lambda\)C | 0.75 0.73 0.55           | 0.08 0.29 0.34          |

The differential and total decay rates for the two–nucleon induced process, \(\Lambda np \rightarrow nnp\), are calculated with the polarization propagator method in local density approximation (LDA) of Refs. [10, 11]. In such a calculation, the simple OPE mechanism, supplemented by strong \(\Lambda N\) and \(NN\) short range correlations (given in terms of phenomenological Landau functions), describes the weak transition process. In the present calculation, the distributions of the nucleons emitted by two–nucleon stimulated decays and the value of \(\Gamma_2\) are properly scaled to maintain the ratio \(\Gamma_2/\Gamma_1\) unchanged: we then use \(\Gamma_2/\Gamma_1 = (\Gamma_2/\Gamma_1)^{\text{LDA}} = 0.20\) for \(^5\Lambda\)He and 0.25 for \(^{12}\Lambda\)C.

2.2. Intranuclear cascade simulation

In their way out of the nucleus, the weak decay (i.e., primary) nucleons continuously change energy, direction and charge due to collisions with other nucleons. As a consequence, secondary nucleons are also emitted.

We simulate the nucleon propagation inside the residual nucleus with the Monte Carlo code of Ref. [23]. A random number generator determines the decay channel, \(n-, p-\) or two–nucleon induced, according to the values of \(\Gamma_n/\Gamma_p\) and \(\Gamma_2/\Gamma_1\) predicted by our finite nucleus and LDA approaches. Positions, momenta and charges of the weak decay nucleons are selected by the same random number generator, according to the corresponding probability distributions given by the finite nucleus and LDA calculations.

Once they are produced, the primary nucleons move under a local potential \(V_N(R) = -k_{F_N}^2(R)/2m_N\), where \(k_{F_N}(R) = [3\pi^2\rho_N(R)]^{1/3} (N = n, p)\) is the local nucleon Fermi momentum corresponding to the nucleon density \(\rho_N(R)\). The primary nucleons also collide with other nucleons of the medium according to free space nucleon–nucleon cross sections [24] properly corrected to take into account the Pauli blocking effect. For further details concerning the intranuclear cascade calculation see Ref. [23]. Each Monte Carlo event ends with a certain number of nucleons which leave the nucleus along defined directions and with defined energies. One can then select the outgoing nucleons and store them in different ways, as we shall do in the discussion of Section 3.

3. RESULTS

The ratio \(\Gamma_n/\Gamma_p\) is defined as the ratio between the number of weak decay \(nn\) and \(np\) pairs, \(N_{nm}^{\text{wd}}\) and \(N_{np}^{\text{wd}}\). However, due to two–body induced decays and (especially) nucleon
Table 2
Predictions for the ratio $R_2 \equiv N_{nn}/N_{np}$ for $^5\Lambda$He and $^{12}\Lambda$C. An energy threshold of 30 MeV and two pair opening angle regions have been considered. The (preliminary) data are from KEK–E462 [19].

|       | $^5\Lambda$He |       | $^{12}\Lambda$C |
|-------|--------------|-------|----------------|
|       | $\cos \theta_{NN} \leq -0.8$ | all $\theta_{NN}$ | $\cos \theta_{NN} \leq -0.8$ | all $\theta_{NN}$ |
| OPE   | 0.25         | 0.26  | 0.24           | 0.29            |
| OMEa  | 0.51         | 0.45  | 0.39           | 0.37            |
| OMEf  | 0.61         | 0.54  | 0.43           | 0.39            |
| EXP   | 0.44 ± 0.11  |       |                |                 |

FSI effects, one expects the following inequality:

$$\frac{\Gamma_n}{\Gamma_p} \equiv \frac{N_{nn}^{wd}}{N_{np}^{wd}} \neq \frac{N_{nn}}{N_{np}} \equiv R_2 [\Delta \theta_{12}, \Delta T_n, \Delta T_p],$$

when the observable numbers $N_{nn}$ and $N_{np}$ are determined by employing particular intervals of variability of the pair opening angle, $\Delta \theta_{12}$, and the nucleon kinetic energies, $\Delta T_n$ and $\Delta T_p$. The results discussed in Ref. [18] clearly show the dependence of $N_{nn}/N_{np}$ on $\Delta \theta_{12}$ and $\Delta T_n$ and $\Delta T_p$. However, $N_{nn}/N_{np}$ turns out to be much less sensitive to FSI effects and variations of the energy cuts and angular restrictions than $N_{nn}$ and $N_{np}$ separately.

The numbers of nucleon pairs $N_{NN}$ —which we consider to be normalized per non-mesonic weak decay— are related to the corresponding quantities for the neutron– ($N_{1Bn}^{1B}$) proton– ($N_{1Bp}^{1B}$) and two–nucleon ($N_{2B}^{2B}$) induced processes via the following equation:

$$N_{NN} = \frac{N_{NN}^{1Bn} \Gamma_n + N_{NN}^{1Bp} \Gamma_p + N_{NN}^{2B} \Gamma_2}{\Gamma_n + \Gamma_p + \Gamma_2} \equiv N_{NN}^{\Lambda n\rightarrow nn} + N_{NN}^{\Lambda p\rightarrow np} + N_{NN}^{\Lambda np\rightarrow npn}.$$  \(\text{(2)}\)

Here, $N_{NN}^{1Bn} \equiv N_{NN}^{\Lambda n\rightarrow nn}/(\Gamma_n + \Gamma_p + \Gamma_2)/\Gamma_n$ is normalized per neutron–induced non–mesonic weak decay, etc. Therefore, $N_{NN}^{1Bn}$, $N_{NN}^{1Bp}$ and $N_{NN}^{2B}$ ($N_{NN}^{\Lambda n\rightarrow nn}$, $N_{NN}^{\Lambda p\rightarrow np}$ and $N_{NN}^{\Lambda np\rightarrow npn}$) do not depend (do depend) on the interaction model employed to describe the weak decay.

In Table 2 the ratio $N_{nn}/N_{np}$ predicted by the OPE, OMEa and OMEf models for $^5\Lambda$He and $^{12}\Lambda$C is given for two opening angle intervals and for $T_n, T_p \geq 30$ MeV. The results of the OMEa and OMEf models are in reasonable agreement with the preliminary KEK–E462 data for $^5\Lambda$He [19].

3.1. A weak interaction model independent analysis of data

We now discuss a weak interaction model independent analysis of KEK coincidence data. To this aim, we make use of the 6 quantities $N_{nn}^{1Bn}$, $N_{nn}^{1Bp}$, $N_{nn}^{2B}$, $N_{np}^{1Bn}$, $N_{np}^{1Bp}$ and $N_{np}^{2B}$ entering Eq. (2): they are quoted in Table 3 and, by definition, do not depend on the
Table 3
Predictions for the weak interaction model independent quantities $N_{nn}^{1Bn}$, $N_{nn}^{1Bp}$, $N_{np}^{1Bn}$, $N_{np}^{1Bp}$ and $N_{np}^{2B}$ (integrated over all angles and for $T_n, T_p \geq 30$ MeV) of Eq. (2) for $^\Lambda_5$He and $^{12}$C. The numbers in parentheses correspond to the angular region with $\cos \theta_{NN} \leq -0.8$.

|          | $N_{nn}^{1Bn}$ | $N_{nn}^{1Bp}$ | $N_{np}^{2B}$ |
|----------|----------------|----------------|---------------|
| $^\Lambda_5$He | 0.84 (0.53) | 0.10 (0.02) | 0.54 (0.34) |
| $^{12}$C     | 0.56 (0.30) | 0.27 (0.05) | 0.30 (0.12) |

|          | $N_{np}^{1Bn}$ | $N_{np}^{1Bp}$ | $N_{np}^{2B}$ |
|----------|----------------|----------------|---------------|
| $^\Lambda_5$He | 0.20 (0.05) | 0.98 (0.49) | 0.55 (0.22) |
| $^{12}$C     | 0.33 (0.08) | 1.22 (0.38) | 0.38 (0.11) |

model used to describe the weak decay. We have thus to employ the following relation:

$$\frac{N_{nn}}{N_{np}} = \frac{\left(N_{nn}^{1Bn} + N_{nn}^{2B} \frac{\Gamma_2}{\Gamma_1}\right) \frac{\Gamma_n}{\Gamma_p} + N_{nn}^{1Bp} + N_{nn}^{2B} \frac{\Gamma_2}{\Gamma_1}}{\left(N_{np}^{1Bn} + N_{np}^{2B} \frac{\Gamma_2}{\Gamma_1}\right) \frac{\Gamma_n}{\Gamma_p} + N_{np}^{1Bp} + N_{np}^{2B} \frac{\Gamma_2}{\Gamma_1}}$$

(3)

using $\Gamma_n/\Gamma_p$ and $\Gamma_2/\Gamma_1$ as fitting parameters.

In Fig. 1 we report the dependence of $N_{nn}/N_{np}$ for $^\Lambda_5$He on $\Gamma_n/\Gamma_p$ for four different values of $\Gamma_2/\Gamma_1$. The figure corresponds to the experimentally interesting case with a nucleon energy threshold of 30 MeV and the angular restriction $\cos \theta_{nn} \leq -0.8$. For a given value of $\Gamma_2/\Gamma_1$, Fig. 1 permits an immediate determination of $\Gamma_n/\Gamma_p$ by a direct comparison with data for the observable $N_{nn}/N_{np}$.

By using the $^\Lambda_5$He data $N_{nn}/N_{np} = 0.44 \pm 0.11$ from KEK–E462 [19] and neglecting the two–nucleon induced mechanism (i.e., $\Gamma_2 = 0$), Eq. (3) supplies:

$$\frac{\Gamma_n}{\Gamma_p} (^\Lambda_5$He$) = 0.39 \pm 0.11$$

(4)

By employing the value $\Gamma_2/\Gamma_1 = 0.2$ (i.e., the one obtained with the model of Ref. [11] and used in the present calculation), a 34% reduction of the ratio is predicted:

$$\frac{\Gamma_n}{\Gamma_p} (^\Lambda_5$He$) = 0.26 \pm 0.11$$

(5)

These results for $\Gamma_n/\Gamma_p$ are in agreement with the pure theoretical predictions of Refs. [5, 6, 13]. On the contrary, they are rather small if compared with previous determinations [20] (0.93 ± 0.55) [21] (1.97 ± 0.67) from single–nucleon spectra analyses. Actually, all the previous experimental analyses of single–nucleon spectra [20, 21, 25], supplemented in some cases by intranuclear cascade calculations, derived $\Gamma_n/\Gamma_p$ values in disagreement with pure theoretical predictions. In our opinion [18], the fact that our calculations reproduce coincidence data for values of $\Gamma_n/\Gamma_p$ as small as 0.3 ± 0.4 could signal the existence of non–negligible interference effects between the $n$– and $p$–induced channels in those old single–nucleon data.
4. CONCLUSIONS

To summarize, our weak interaction models supplemented by FSI through an intranuclear cascade simulation provide double–coincidence observables which are in reasonable agreement with preliminary KEK–E462 data for $^5\Lambda$He. Through a weak interaction model independent analysis in which $\Gamma_n/\Gamma_p$ and $\Gamma_2/\Gamma_1$ are free parameters we reproduce the KEK $^5\Lambda$He data $N_{nn}/N_{np} = 0.44 \pm 0.11$ if $\Gamma_n/\Gamma_p = 0.39 \pm 0.11$ and $\Gamma_2 = 0$ or $\Gamma_n/\Gamma_p = 0.26 \pm 0.11$ and $\Gamma_2/\Gamma_1 = 0.2$. Although these values of $\Gamma_n/\Gamma_p$ extracted from data agree with other recent pure theoretical evaluations (such an agreement has been achieved now for the first time), they are rather small if compared with the results of previous analyses from single–nucleon spectra. We suspect that non–negligible interference effects between the neutron– and proton–induced channels affected those single–nucleon analyses.

In conclusion, although further (theoretical and experimental) work is needed, we think that our investigation proves how the study of nucleon coincidence observables can offer a promising possibility to solve the longstanding puzzle on the $\Gamma_n/\Gamma_p$ ratio.
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