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Nuclear Physics A 914 (2013) 204–208

NUCLEAR PHYSICS A

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Microscopic model to nucleon spectra in hypernuclear non-mesonic weak decay

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Received 29 November 2012; received in revised form 27 December 2012; accepted 28 December 2012

Available online 8 January 2013

Abstract

A consistent microscopic model is applied to the calculation of the nucleon emission spectra in the non-mesonic weak decay of Λ-hypernuclei. We adopt a nuclear matter formalism extended to finite nuclei via the local density approximation, a one-meson exchange weak transition potential and a Bonn nucleon–nucleon strong potential. Ground state correlations and final state interaction, at second order in the nucleon–nucleon interaction, are introduced on the same footing for all the isospin channels of one- and two-nucleon induced decays. Double-coincidence nucleon spectra are predicted for $^{12}_{\Lambda}C$ and compared with recent KEK data. Discrepancies with data remain for proton emission and for both neutron–proton and neutron–neutron emission in the non-back-to-back kinematics region. Motivated by a recent triple-coincidence measurement by FINUDA, we estimate the three-body induced decay, where we have found, $\Gamma_3/\Gamma_2 \cong 0.23$. Our microscopic model also predicts values for the asymmetry parameter in $^{12}_{\Lambda}C$, consistent with the asymmetry measured at KEK.

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Keywords: Λ-hypernuclei; Non-mesonic weak decay; Two-nucleon induced decay; FSI

1. Introduction

In recent years some very interesting new measurements were carried out for the non-mesonic weak decay of Λ-hypernuclei. In particular, we refer to the recent experiments carried out at KEK [1–4] and FINUDA [5,6]. These advances were accompanied by the advent of elaborated theoretical models (some of which included final state interactions and ground state correlation effects on the same ground) and allowed us to reach a reasonable agreement between data and

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http://dx.doi.org/10.1016/j.nuclphysa.2012.12.127

predictions for the non-mesonic weak decay rates and asymmetry parameters (for a recent review see [7]).

Beyond these improvements, there are still discrepancies between theory and experiment for the emission spectra involving protons [8–10]. In fact, while the neutron emission spectra are rather well reproduced by theoretical models, the same does not happen for proton spectra. In this case, the theoretical predictions overestimate data. In order to try to understand this problem, we have developed a microscopic model, where nucleon final state interactions (FSI) and ground state correlations (GSC) can be included on the same footing in the calculation of decay widths and nucleon emission spectra (see [9,10], and references therein). In a recent contribution [10], we have explored the effect of the $\Delta(1232)$-baryon resonance on the nucleon emission spectra. The Δ introduces new FSI-induced decay mechanisms which lead to an improvement when comparing the obtained nucleon spectra with data, while it turns out to have a negligible effect on the decay rates. However, the discrepancies with data still remain, but are mostly restricted to the non-back-to-back kinematics.

In a recent work, M. Agnello et al. [11], have reported the first triple-coincidence measurement events, where the distinction between back-to-back and non-back-to-back kinematics is less relevant. In the present contribution, we overview the status of the microscopic model and evaluate a new theoretical ingredient needed for the prediction of triple-coincidence spectra.

2. Formalism

As long as we limit the final state to three nucleons, the non-mesonic decay width, $\Gamma_{\mathrm{NM}} = \Gamma_1 + \Gamma_2$, is built up from one- (1N) and two-nucleon induced (2N) decays, $\Gamma_1 = \Gamma_n + \Gamma_p$ and $\Gamma_2 = \Gamma_{nn} + \Gamma_{np} + \Gamma_{pp}$, where the isospin components are given by $\Gamma_N = \Gamma(\Lambda N \to nN)$ and $\Gamma_{NN'} = \Gamma(\Lambda N N' \to nNN')$, with $N, N' = n$ or p. In this case, we can write the total number of nucleons and nucleon pairs emitted in the non-mesonic decay as follows [12]:

$$N_n = 2\bar{\Gamma}_n + \bar{\Gamma}_p + 3\bar{\Gamma}_{nn} + 2\bar{\Gamma}_{np} + \bar{\Gamma}_{pp} + \sum_{i,f} N_{f(n)}\bar{\Gamma}_{i,f}, \tag{1}$$

$$N_p = \bar{\Gamma}_p + \bar{\Gamma}_{np} + 2\bar{\Gamma}_{pp} + \sum_{i,f} N_{f(p)}\bar{\Gamma}_{i,f}, \tag{2}$$

$$N_{nn} = \bar{\Gamma}_n + 3\bar{\Gamma}_{nn} + \bar{\Gamma}_{np} + \sum_{i,f} N_{f(nn)}\bar{\Gamma}_{i,f}, \tag{3}$$

$$N_{np} = \bar{\Gamma}_p + 2\bar{\Gamma}_{np} + 2\bar{\Gamma}_{pp} + \sum_{i,f} N_{f(np)}\bar{\Gamma}_{i,f}, \tag{4}$$

$$N_{pp} = \bar{\Gamma}_{pp} + \sum_{i,f} N_{f(pp)}\bar{\Gamma}_{i,f}, \tag{5}$$

where a normalization per non-mesonic decay is used ($\bar{\Gamma} \equiv \Gamma/\Gamma_{\mathrm{NM}}$). The $\bar{\Gamma}_N$'s ($\bar{\Gamma}_{NN'}$'s) denote the 1N (2N) decay rates, while the terms containing the functions $\bar{\Gamma}_{i,f}$ represent the FSI effects. In practice, one proposes some sub-set of Goldstone diagrams, which are employed in the evaluation of all $\bar{\Gamma}$'s. The ones chosen in this contribution are depicted in Fig. 1 in [9,10]. The index i in $\bar{\Gamma}_{i,f}$ is used to label the various FSI Goldstone diagrams included in the present calculation. Finally, $N_{f(N)}$ ($N_{f(NN')}$) is the number of nucleons of the type N (of NN' pairs) contained in the multinucleon state f. Single and double coincidence nucleon spectra are obtained by constraining the evaluation of each $\bar{\Gamma}$ to certain intervals in energy, opening angle, etc.

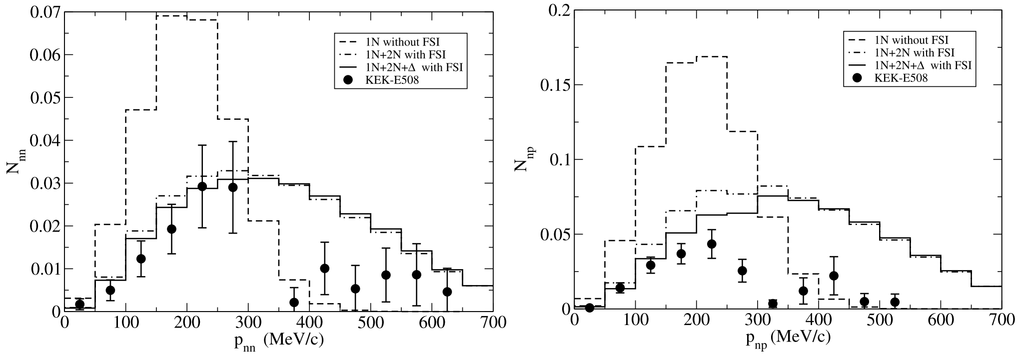

Fig. 1. Momentum correlation spectra of nn and np pairs, with $p_{NN'} \equiv |\vec{p}_N + \vec{p}_{N'}|$. Data are from KEK-E508 [4].

As a further improvement, in the present contribution we introduce the three-nucleon induced (3N) decay, $\Gamma_3 = \Gamma_{nnn} + \Gamma_{nnp} + \Gamma_{npp} + \Gamma_{ppp}$, where the isospin components are given by $\Gamma_{NN'N''} = \Gamma(\Lambda NN'N'' \to nNN'N'')$, with N, N', $N'' = n$ or p. This adds a new term to the non-mesonic decay width, which reads now $\Gamma_{\mathrm{NM}} = \Gamma_1 + \Gamma_2 + \Gamma_3$. The Γ_3 terms must be included in Eqs. (1)–(5) and triple nucleons are given by,

$$N_{nnn} = \bar{\Gamma}_{nn} + 4\bar{\Gamma}_{nnn} + \bar{\Gamma}_{nnp} + \sum_{i,f} N_{f(nnn)}\bar{\Gamma}_{i,f}, \tag{6}$$

$$N_{nnp} = \bar{\Gamma}_{np} + 3\bar{\Gamma}_{nnp} + 2\bar{\Gamma}_{npp} + \sum_{i,f} N_{f(nnp)}\bar{\Gamma}_{i,f}, \tag{7}$$

$$N_{npp} = 2\bar{\Gamma}_{npp} + \sum_{i,f} N_{f(npp)}\bar{\Gamma}_{i,f}, \tag{8}$$

$$N_{ppp} = \bar{\Gamma}_{ppp} + \sum_{i,f} N_{f(ppp)}\bar{\Gamma}_{i,f}. \tag{9}$$

This represents a natural extension of the already discussed microscopic model in view of a possible measurement of triple-coincidence spectra.

3. Results

In this section we reproduce some results for the nucleon emission spectra and we present for the first time values for Γ_3. We adopt a one-meson exchange weak transition potential, a Bonn nucleon–nucleon strong potential and a nuclear matter formalism extended to finite nuclei via the local density approximation. In particular, we evaluate the ${}^{12}_{\Lambda}$C non-mesonic weak decay.

In Fig. 1, we give the two-nucleon momentum correlation spectra, i.e., the nn and np distributions as a function of the momentum sum $p_{NN'} \equiv |\vec{p}_N + \vec{p}_{N'}|$ of two of the outgoing nucleons. The dashed lines correspond to the 1N decay; the dot-dashed curves refer to the results with 1N, 2N and FSI included; finally, the continuous curves show the full, "1N + 2N + Δ with FSI" predictions. Both the "1N + 2N with FSI" and "1N + 2N + Δ with FSI" calculations are performed by considering a nucleon kinetic energy threshold $T_N^{\mathrm{th}} = 30$ MeV, as in the data also shown in the figures. For a detailed discussion on these figures, we refer the reader to [10]. There is a rather good agreement between theory and experiment for both nn and np at low $p_{NN'}$-values (consistent with back-to-back kinematics). In the non-back-to-back region, a discrepancy is present of

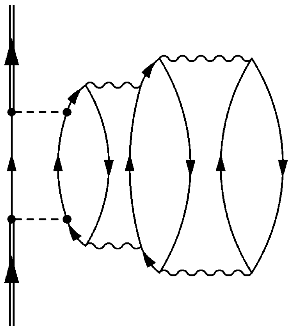

Fig. 2. The Goldstone diagram employed to evaluate Γ_3. In this diagram a double-arrow represents the Λ, while an up (down) going arrow is a nucleon particle (hole). The dashed (wiggly) line is the weak transition potential (strong interaction).

both nn and np, but it is significantly worse for np. Due to the required consistency among data, the disagreement shown here for nn must be hidden in the particular way of presenting data. For instance, in a plot of single-neutron emission vs. kinetic energy, theory reproduces rather well the experimental points. For kinetic energies beyond the $T_N^{\rm th} = 30$ MeV-energy threshold, theory overestimates data by a small amount [10] (but reproducing data within error bars). Clearly, one source of this small disagreement should be ascribed to the 'dip' region shown in Fig. 1. As it is noted in [4], the minimum in both the nn and np KEK-E508 distributions is an effect of the low statistics and detection efficiency for events with $p_{NN'} \gtrsim 350$ MeV/c (the KEK detector geometry being optimized for back-to-back coincidence events, i.e., for small values of $p_{NN'}$). In any case, there are two sources of discrepancy between theory and experiment: the first one is the spectra involving protons and the second one is the spectra in the non-back-to-back region (for both neutron–proton and neutron–neutron distributions).

Let us emphasize that the microscopic model is a fully quantum-mechanical scheme, which naturally accounts for quantum interference terms (QIT) that play a very important role. The reduction seen in the free spectra in Fig. 1, for small values of $p_{NN'}$ when FSI are implemented, requires a negative contribution which can only be a QIT. Also, it should be mentioned that the microscopic model predicts values for the asymmetry parameter in ${}^{12}_{\Lambda}$C [13], consistent with the asymmetry measured at KEK.

The eventual measurement of triple-coincidence spectra would certainly be very helpful in understanding the disagreement between theory and experiment. In first place, the preference on the back-to-back kinematics is particular to two-nucleon coincidence events. In second place, and from the theoretical side, this spectra is strongly dependent on the FSI-model employed for its evaluation, meaning that it is a good test for the scheme. In order to make predictions on these spectra, one has to evaluate Γ_3. In this work we have evaluated Γ_3 from Fig. 2 (we have chosen this diagram based on previous experience which suggests that this should be the dominant contribution). We have obtained, $\Gamma_3/\Gamma_2 \cong 0.23$, with the following relative isospin contributions, $(\Gamma_{nnn}/\Gamma_3) : (\Gamma_{nnp}/\Gamma_3) : (\Gamma_{npp}/\Gamma_3) : (\Gamma_{ppp}/\Gamma_3) = 0.01 : 0.55 : 0.42 : 0.02$. We refer the reader to [9] for the Γ_1 and Γ_2 values. A more accurate evaluation of Γ_3, requires more diagrams and will be published elsewhere. This preliminary evaluation give us a lower limit for Γ_3, it tells us that it has some relevance in the evaluation of Γ_{NM} and that it is important in the evaluation of the triple-coincidence spectra. Note that a negligible result for Γ_3, would indicate a peak-shaped distribution for the spectra, plotted as a function of the sum of the kinetic energy of the emitted nucleons. The Γ_3 plus all four nucleon emission from FSI spread this peak-shaped distribution.

4. Conclusions

Summarizing, a microscopic approach including GSC and FSI on the same footing is used to evaluate the nucleon emission spectra in non-mesonic weak decay of hypernuclei. Within our microscopic model, QIT play a key role. However, there are two discrepancies with experiment which remain: spectra involving protons and the spectra corresponding to the non-back-to-back kinematics, for both neutron–proton and neutron–neutron pairs. Further work is in order to understand these disagreements. In particular, the recent measurement of triple-coincidence events are encouraging. In the present contribution we have shown the first prediction of Γ_3, which is needed for an accurate theoretical evaluation of triple-coincidence spectra. Our result shows that Γ_3 cannot be neglected. Finally, it has been mentioned that the microscopic model gives values for the asymmetry parameter in agreement with data.

Acknowledgements

I thank G. Garbarino for the fruitful discussions and for the careful reading of the manuscript. This work has been partially supported by the CONICET and ANPCyT, Argentina, under contracts PIP 0032 and PICT-2010-2688, respectively.

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