Microscopic Model to Nucleon Spectra in Hypernuclear Non–Mesonic Weak Decay

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Outline of the talk

- Introduction to $\Lambda$-Weak Decay in Hypernuclei
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- Theoretical Framework: the Microscopic Model
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- Results & Comparison with Data
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- Results & Comparison with Data
- Conclusions
Weak decay modes of $\Lambda$-hypernuclei

Mesonic decay,

$$\Gamma_M = \Gamma_{\pi^-} + \Gamma_{\pi^0},$$

- dominant in free space
- blocked by Pauli Principle

Non-Mesonic decay,

$$\Gamma_{NM} = \Gamma_{NM}(\Lambda N \rightarrow nN)$$

- only in hypernuclei
- dominant for medium and heavy hypernuclei

$$\Gamma_T = \Gamma_M + \Gamma_{NM}$$
Non-mesonic weak decay

**One-nucleon induced:** \( \Gamma_1(\Lambda N \rightarrow nN) \),

\[
\Gamma_1 \equiv \Gamma_n(\Lambda n \rightarrow nn) + \Gamma_{p}(\Lambda p \rightarrow np)
\]

**Two-nucleon induced:** \( \Gamma_2(\Lambda NN \rightarrow nNN) \),

\[
\Gamma_2 \equiv \Gamma_{nn}(\Lambda nn \rightarrow nnn) + \Gamma_{np}(\Lambda np \rightarrow nnp) + \Gamma_{pp}(\Lambda pp \rightarrow npp)
\]

\[
\Gamma_{NM} = \Gamma_1 + \Gamma_2
\]
The non-mesonic decay width

Fermi Golden Rule:

\[ \Gamma_{NM} = \sum_f |\langle f|V^{\Lambda N \rightarrow NN}|0\rangle|^2 \delta(E_f - E_0) \]
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|0\>: hypernuclear ground state, with energy \( E_0 \)
The non-mesonic decay width

Fermi Golden Rule:

\[ \Gamma_{NM} = \sum_f |\langle f | V^{\Lambda N \rightarrow NN} | 0 \rangle|^2 \delta(E_f - E_0) \]

- \(|0\rangle\): hypernuclear ground state, with energy \(E_0\)
- \(V^{\Lambda N \rightarrow NN}\): two-body weak transition potential, including the exchange of the complete octets of pseudoscalar and vector mesons (\(\pi, \eta, K, \rho, \omega\) and \(K^*\))
The non-mesonic decay width

Fermi Golden Rule:

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- \( |0\rangle \): hypernuclear ground state, with energy \( E_0 \)
- \( V^{AN \rightarrow NN} \): two-body weak transition potential, including the exchange of the complete octets of pseudoscalar and vector mesons (\( \pi, \eta, K, \rho, \omega \) and \( K^* \))
- \( |f\rangle \): final state, with energy \( E_f \)
  - \( |f\rangle = |2p1h\rangle \) for \( \Gamma_1 \)
  - \( |f\rangle = |3p2h\rangle \) for \( \Gamma_2 \)
A simple model,

\[ N_n = 2\Gamma_n + \Gamma_p \quad \text{and} \quad N_{nn} = \Gamma_n \]
\[ N_p = \Gamma_p \quad \text{and} \quad N_{np} = \Gamma_p \]

from these expressions one can write,

\[ \frac{\Gamma_n}{\Gamma_p} = \frac{1}{2} \left( \frac{N_n}{N_p} - 1 \right) \quad \text{or} \quad \frac{\Gamma_n}{\Gamma_p} = \frac{N_{nn}}{N_{np}} \]

The next step is to add

\[ \Gamma_2 \equiv \Gamma_{nn} + \Gamma_{np} + \Gamma_{pp}, \]

where, \( \bar{\Gamma} \equiv \Gamma / \Gamma_{NM} \)
Adding $\Gamma_2$,

\[ N_n = 2\bar{\Gamma}_n + \bar{\Gamma}_p + 3\bar{\Gamma}_{nn} + 2\bar{\Gamma}_{np} + \bar{\Gamma}_{pp}, \]
\[ N_p = \bar{\Gamma}_p + \bar{\Gamma}_{np} + 2\bar{\Gamma}_{pp}, \]
\[ N_{nn} = \bar{\Gamma}_n + 3\bar{\Gamma}_{nn} + \bar{\Gamma}_{np}, \]
\[ N_{np} = \bar{\Gamma}_p + 2\bar{\Gamma}_{np} + 2\bar{\Gamma}_{pp}, \]
\[ N_{pp} = \bar{\Gamma}_{pp}. \]

Up to this point, the decay widths ($\Gamma$'s) can be extracted straightaway from the spectra.

But now we add FSI:

\[ N_n = 2\bar{\Gamma}_n + \bar{\Gamma}_p + ... + FSI, \]
Microscopic model for $N_N$ and $N_{NN}$

\[
N_n = 2\tilde{\Gamma}_n + \tilde{\Gamma}_p + 3\tilde{\Gamma}_{nn} + 2\tilde{\Gamma}_{np} + \tilde{\Gamma}_{pp} + \sum_{i, i'; j} N_j (n) \tilde{\Gamma}_{i, i' \rightarrow j},
\]

\[
N_p = \tilde{\Gamma}_p + \tilde{\Gamma}_{np} + 2\tilde{\Gamma}_{pp} + \sum_{i, i'; j} N_j (p) \tilde{\Gamma}_{i, i' \rightarrow j},
\]

\[
N_{nn} = \tilde{\Gamma}_n + 3\tilde{\Gamma}_{nn} + \tilde{\Gamma}_{np} + \sum_{i, i'; j} N_j (nn) \tilde{\Gamma}_{i, i' \rightarrow j},
\]

\[
N_{np} = \tilde{\Gamma}_p + 2\tilde{\Gamma}_{np} + 2\tilde{\Gamma}_{pp} + \sum_{i, i'; j} N_j (np) \tilde{\Gamma}_{i, i' \rightarrow j},
\]

\[
N_{pp} = \tilde{\Gamma}_{pp} + \sum_{i, i'; j} N_j (pp) \tilde{\Gamma}_{i, i' \rightarrow j}.
\]

where, $\tilde{\Gamma} \equiv \Gamma / \Gamma_{NM}$

Employed Feynman diagrams

Without FSI

$$|f\rangle = |2p1h\rangle$$

With FSI

$$|f\rangle = |2p1h\rangle$$

or

$$|f\rangle = |3p2h\rangle$$
The $pp$-Feynman diagram,

expressed in terms of its sum of Goldstone diagrams:
FSI from the $\Delta(1232)$,

These are Goldstone diagrams,
Results & Comparison with Data

\[ V^{\Lambda N \rightarrow NN} \] is represented by the exchange of the \( \pi, \eta, K, \rho, \omega \) and \( K^* \) mesons, with the coupling constants and cut–off parameters deduced from the Nijmegen soft–core interaction NSC97f of V. G. J. Stoks and Th. A. Rijken, Phys. Rev. C 59 (1999) 3009; Th. A. Rijken, V. G. J. Stoks and Y. Yamamoto, ibid. 59 (1999) 21.

For \( V^{NN \rightarrow NN} \) we adopt the Bonn potential (with the exchange of \( \pi, \rho, \sigma \) and \( \omega \) mesons), R. Machleidt, K. Holinde and Ch. Elster; Phys. Rep. 149 (1987) 1.

For \( V^{NN \rightarrow \Delta N} \) we have used a \( V_{\pi+\rho} \)-potential with the addition of a \( g'_{\Delta N} \)-Landau-Migdal parameter. (See for instance, E. Oset, H. Toki and W. Weise, Phys. Rept. 83 (1982) 281). We have used, \( g'_{\Delta N} = 0.4 \).
Single nucleon spectra

Opening angle distribution of $nn$ and $np$ pairs

Momentum correlation spectra, $\rho_{NN'} \equiv |\vec{p}_N + \vec{p}_{N'}|$.

Momentum correlation spectra for the sum of the $nn$ and $np$ pair numbers for the back-to-back ($\cos \theta_{NN} < -0.7$) and non back-to-back kinematics ($\cos \theta_{NN} > -0.7$).

KEK-E508: H. Bhang and M. Kim, private communication.
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.
Conclusions

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QIT play a key role: in the single–nucleon emission spectra they are responsible for moving intensity from the high–energy region to the low–energy region, while in the opening angle distribution of nucleon pairs the strong reduction of the back–to–back peak is entirely due to QIT.
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Among the Goldstone diagrams incorporating the $\Delta$, the relevant ones are QIT and turn out to produce a sensitive reduction of the spectra.
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Discrepancies with experiment remain, but are relegated to spectra involving protons.
The next steps:

In M. Agnello et al. (FINUDA Collaboration) Nucl. Phys. A881 (2012) 322, the first triple coincidence measurement has been reported.
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Evaluation of $\Gamma_3 \equiv \Gamma(\Lambda N_1 N_2 N_3 \rightarrow n N_1 N_2 N_3)$ to get some insight on the importance of four particles emission.
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Evaluation of the three particle coincidence spectra.
### Table I: Asymmetry parameter for $^{12}\Lambda C$.

<table>
<thead>
<tr>
<th>$E_{th}$ (MeV)</th>
<th>Asymmetry</th>
<th>Nijmegen89</th>
<th>Nijmegen97f</th>
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<tr>
<td></td>
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<td>OME</td>
<td>OME+2π</td>
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<tr>
<td>0</td>
<td>$a^{1N}_{\Lambda}$</td>
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<tr>
<td>0</td>
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<tr>
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<td>$a^{1N+FSI}_{\Lambda}$</td>
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<td></td>
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<td>$a^{1N+FSI}_{\Lambda}$</td>
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<td>$a^{1N+2N+FSI}_{\Lambda}$</td>
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<tr>
<td>KEK–E508</td>
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<td>-0.16 ± 0.28$^{+0.18}_{-0.00}$</td>
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