Experimental studies on the weak decay of Λ-hypernuclei

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Mission accomplished

1st, direct experimental evidence for $2N$-induced NMWD

1st, experimental assignment of $J_n(^{15}N_\Lambda)=3/2^+$

determination of the $\Gamma_{2\pi}^\Lambda$

1st determination of $\Gamma_p^\Lambda/\Gamma_\Lambda$ for $8$ Hypernuclei
Outline

- The FINUDA apparatus @ INFN/LNF DAΦNE: a detector designed for decay of hypernuclei study
- A revisited analysis of the proton spectra from NMWD of Λ–hypernuclei
- First determination of $\Gamma_p/\Gamma_\Lambda$ for 8 Λ–hypernuclei ($A = 5-16$)
- Determination of the full set of NMWD widths for $^5_{\Lambda}$He and $^{11}_{\Lambda}$B
- A look to the future
**FINUDA in a nutshell**

- **$\text{e}^- + \text{e}^+ \rightarrow \phi \rightarrow \text{K}^- \text{K}^+$**
- **$K^- \text{stop} + ^A_Z \rightarrow ^A_{\Lambda} Z + \pi^-$**

**Summary of Key Parameters**

- **Energy**: $510 \text{ MeV}$
- **Luminosity**: $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- $\sigma_x (\text{rms})$: 2.11 mm
- $\sigma_y (\text{rms})$: 0.021 mm
- $\sigma_z (\text{rms})$: 35 mm
- **Bunch Length**: 30 mm
- **Crossing Angle**: 12.5 mrad
- **Frequency (max)**: 368.25 MHz
- **Bunch/Ring**: up to 120
- **Particle/Bunch**: $8.9 \times 10^{10}$
- **Current/Ring**: 5.2 A (max)
FINUDA key features

- very thin nuclear targets \((0.1 \div 0.3 \text{ g/cm}^2)\)
  - high resolution spectroscopy

- coincidence measurements with large acceptance \((2\pi \text{ sr})\)
  - decay mode study

- event by event \(K^+\) tagging
  - continuous energy and rate calibration

- irradiation of different targets in the same run
  - systematic error reduction
Physics motivations

- lifetime of (light) $\Lambda$-hypernuclei
- check of the validity of the $\Delta I=1/2$ rule

✓ MWD decay exploited as indirect spectroscopic analysis tool

✓ the NMWD study provides the only practical means of exploring the four-fermion, strangeness changing $N\Lambda \rightarrow N\Xi N$ weak interaction

✓ $\Gamma_n/\Gamma_p$ puzzle

✓ experimental evidence of $2\Omega N$-induced process

✓ in medium modifications of hyperons weak decay

✓ ...

see Tuesday’s topical session
Physics output \((S = -1)\)

3. M. Agnello et al., NPA 881 (2012) 269
4. M. Agnello et al., PRC 86 (2012) 057301

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nuclear models

neutron-rich \(\Lambda\)-hypernuclei

spectroscopy

(weak) decay

medium effect

quark substructures

low-energy \(N-Y\) interaction

deeply bound \(K\) states

4B weak interaction

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1. M. Agnello et al., PRL 94 (2005) 212303

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possible thanks to apparatus performance and stability

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2. M. Agnello et al., PLB 681 (2009) 139
4. M. Agnello et al., PLB 698 (2011) 219
5. M. Agnello et al., PLB 701 (2011) 556
7. M. Agnello et al., PLB 738 (2014) 499
8. E. Botta et al., PLB 748 (2015) 86
Observables in Weak Decay of $\Lambda$–Hypernuclei

\[ \Gamma_T = \frac{\hbar}{\tau_{\text{hyp}}} \]

\[ {}^A_Z \Lambda \rightarrow {}^{A_2}(Z+1) + \pi^- \quad {}^A_Z \Lambda \rightarrow {}^{A_0}Z + \pi^0 \]

\[ \Lambda \rightarrow p + \pi^- \quad \Lambda \rightarrow n + \pi^0 \]

\[ {}^A_Z \Lambda \rightarrow {}^{(A_2)}(Z-1) + n + p \quad {}^A_Z \Lambda \rightarrow {}^{(A_2)}Z + n + n \]

\[ \Lambda + p \rightarrow n + p \quad \Lambda + n \rightarrow n + n \]

\[ {}^A_Z \Lambda \rightarrow {}^{(A_3)}(Z-2) + n + p + p \quad {}^A_Z \Lambda \rightarrow {}^{(A_3)}(Z-1) + n + n + p \]

\[ \Lambda + p + p \rightarrow n + p + p \quad \Lambda + n + p \rightarrow n + n + p \]

\[ \Lambda + n + n \rightarrow n + n + n \]
Anatomy of NMWD p spectra

$p$ spectra background subtracted and acceptance corrected

1σ/$N$, 2σ/$N$, FSI!!!

15 MeV threshold!

common features:
- structure at ~80 MeV
- low energy rise


Revisited analysis of the proton spectra

Attempt of improving the fits by shifting down the lower edge for the fits to 50, 60 and 70 MeV:

better value of $\chi^2/n = 1.33$ when choosing the starting point at 70 MeV.
The central values of the fitting Gaussians ($\mu$) were used to divide the full area of the proton spectra into two regions, $A_{\text{low}}$ and $A_{\text{high}}$. It was shown that from the expression:

\[ R_1(A) = \frac{A_{\text{low}}(A)}{A_{\text{low}}(A) + A_{\text{high}}(A)} \]

the ratio $\Gamma_{2^+}/\Gamma_p$ can be obtained (under the assumption that it is constant in the range $A = 5 \div 16$).

It was found (single particle spectra):

\[ \Gamma_{2^+}/\Gamma_p = 0.43 \pm 0.25 \quad (\Gamma_{2^+}/\Gamma_{\text{NMWD}} = 0.24 \pm 0.10) \]

With the new values we find:

\[ \Gamma_{2^+}/\Gamma_p = 0.50 \pm 0.24 \quad (\Gamma_{2^+}/\Gamma_{\text{NMWD}} = 0.25 \pm 0.12) \]

compatible with the previous one, within the errors.
**Refined determination of** $\frac{\Gamma_{2N}}{\Gamma_{NMWD}}$

By selecting $(n,p)$ coincidence events we found:

$$\frac{\Gamma_{2N}}{\Gamma_p} = 0.39 \pm 0.16^{+0.04}_{-0.03} \text{stat}$$

$$\left( \frac{\Gamma_{2N}}{\Gamma_{NMWD}} = 0.21 \pm 0.07^{+0.03}_{-0.02} \text{stat} \right)$$

With the new $\mu$ values, we got:

$$\frac{\Gamma_{2N}}{\Gamma_p} = 0.36 \pm 0.14^{+0.05}_{-0.04} \text{stat}$$

$$\left( \frac{\Gamma_{2N}}{\Gamma_{NMWD}} = 0.20 \pm 0.08^{+0.03}_{-0.02} \text{stat} \right)$$

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Fully compatible with the previous one, within the errors.
Some information can be extracted by the proton spectra, but how it is possible to extract the “true” number of protons from NMWD. Spectra are severely distorted by several FSI effects.

At least 3 effects:

a) number of primary protons from NMWD decreased by FSI
b) in a given region of the spectrum increase due to the FSI not only of higher energy protons, but of neutrons as well
c) quantum mechanical interference effect

In the upper part of the experimental spectrum b) and c) are negligible

How to calculate a) without resorting to any INC models, but only from experimental data?
First determination of $\Gamma_p/\Gamma_\Lambda$ for 8 Hypernuclei

$$\frac{\Gamma_p}{\Gamma_\Lambda} = \frac{\Gamma_T}{\Gamma_\Lambda} \frac{2(N_p - N_{2N}) + \alpha(N_p - N_{2N})}{N_{\text{Hyp}}}$$

where $\alpha$ accounts for FSI:

$$\left(\frac{\alpha}{2 + \alpha}\right) \text{protons lost}$$

$\alpha$ scales linearly with $A$

$\bar{\alpha}_5(^{5}\text{He}_\Lambda) = 1.15 \pm 0.26$

$\bar{\alpha}_5(^{12}\text{C}_\Lambda) = 1.04 \pm 0.19$

$\bar{\alpha}_{12}(^{12}\text{C}_\Lambda) = 2.48 \pm 0.46$

$\bar{\alpha}_{12}(^{5}\text{He}_\Lambda) = 2.77 \pm 0.63$

$\bar{\alpha}_5 = 1.08 \pm 0.16$

$\bar{\alpha}_{12} = 2.58 \pm 0.37$

$\alpha(A) = (0.215 \pm 0.031) \cdot A$
First determination of $\Gamma_p/\Gamma_\Lambda$ for 8 Hypernuclei

$\Gamma_p/\Gamma_\Lambda$ vs mass number (A)

- FINUDA
- J.J. Szymanski et al.
- H. Noumi et al.
- H. Bhang et al.
- K. Itonaga, T. Motoba


M. Agnello et al., PLB 738 (2014) 499.
H. Bhang et al., JKPS 59 (2011) 1461.
First determination of $\Gamma_p / \Gamma_\Lambda$ for 8 Hypernuclei

First determination of $\Gamma_p / \Gamma_\Lambda$ for 8 Hypernuclei


strong nuclear structure effects
Completion of decay pattern for $^5\text{He}_\Lambda$ and $^{11}\text{B}_\Lambda$

<table>
<thead>
<tr>
<th></th>
<th>$^5\text{He}_\Lambda$</th>
<th>$^{11}\text{B}_\Lambda$</th>
<th>$^{12}\text{C}_\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_T/\Gamma_\Lambda$</td>
<td>0.962±0.034</td>
<td>1.274±0.072</td>
<td>1.241±0.041</td>
</tr>
<tr>
<td>$\Gamma_{\pi^-}/\Gamma_\Lambda$</td>
<td>0.342±0.015</td>
<td>0.228±0.027</td>
<td>0.120±0.014</td>
</tr>
<tr>
<td>$\Gamma_{\pi^0}/\Gamma_\Lambda$</td>
<td>0.201±0.011</td>
<td>0.192±0.056</td>
<td>0.165±0.008</td>
</tr>
<tr>
<td>$\Gamma_p/\Gamma_\Lambda$</td>
<td>0.217±0.041</td>
<td>0.47±0.11</td>
<td>0.493±0.088</td>
</tr>
<tr>
<td>$\Gamma_{2N}/\Gamma_\Lambda$</td>
<td>0.078±0.034</td>
<td>0.169±0.077</td>
<td>0.178±0.076</td>
</tr>
<tr>
<td>$\Gamma_n/\Gamma_\Lambda$</td>
<td>0.125±0.066</td>
<td>0.21±0.16</td>
<td>0.28±0.12</td>
</tr>
<tr>
<td>$\Gamma_n/\Gamma_p$</td>
<td>0.58±0.32</td>
<td>0.46±0.37</td>
<td>0.58±0.27</td>
</tr>
</tbody>
</table>

K. Itonaga, T. Motoba, PTP 185 (2010) 252

$\Gamma_{2N}/\Gamma_p = 0.36 ± 0.14^{+0.05}_{-0.04}\text{sys}$

B. H. Kang et al., J. KPS 59 (2011) 1461

H. Bhung et al., J. KPS 59 (2011) 1461

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

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one order of magnitude more efficient data collection expected with respect to K1.8 beam line

old (2008) conservative (?) perspective

E10 published data: $> 1 \times 10^7 \pi^+/\text{spill}$
A possible apparatus concept layout

unavoidably biased by the FINUDA experience

Cylindrical Detector System

(K1.8BR spectrometer)

essential requirements

- magnetic analysis of decay products
- large detection solid angle ($\sim 2\pi$)
- low detection threshold

SKS magnet

(K1.8 spectrometer)
A possible apparatus concept layout

- Target thickness: ~0.7 gr/cm²
- Along the beam: >1.0 gr/cm²
Expected rates (rough estimate)

- Educated guess
- Interspill: 3.5 s
- From previous experience

\[ \sim 10^8 \pi^+ / \text{spill} \]
\[ \sim 10^{12} \pi^+ / \text{day} \]
\[ \sim 10^4 \, ^{12}\text{C}_\Lambda \text{ g.s.} / \text{day} \]

\[ \sim 1 \, ^{12}\text{C}_\Lambda \text{ g.s.} / 10^8 \pi^+ \]
Formation rate on 1 g/cm² target

B.R. (0.5), \( \Delta \Omega \) (0.5), \( \varepsilon_{\text{riv/rec}} \) (0.5)

E18 request: 4 \( \times \) \( 10^{12} \pi^+ \) on target(s)

- Required beam time: 10 days

- \( \sim 10^4 p \) from \( ^1\!N \rightarrow \) 1% on \( \Gamma_p/\Gamma_\Lambda, \Gamma_\pi/\Gamma_\Lambda \)
- \( \sim 4 \times 10^3 p \) from \( ^2\!N \rightarrow \) 2% on \( \Gamma_2^\pi/\Gamma_\Lambda \)
- \( \sim 10^3 \pi^- \rightarrow \) 3% on \( \Gamma^-/\Gamma_\Lambda \)
- \( \sim 4 \times 10^2 \pi^0 \rightarrow \) 5% on \( \Gamma_\pi^0/\Gamma_\Lambda \)
Conclusions

First systematic determination of $\Gamma_p / \Gamma_\Lambda$ for $p$-shell Hypernuclei

Experimental data agree with the latest calculations by Itonaga & Motoba, (even though the errors are quite large...)

First experimental verification of the complementary between MWD and NMWD, at least for charged channels

Completion of $^5\text{He}_\Lambda$ and $^{11}\text{B}_\Lambda$ NMWD pattern

Looking forward for new opportunities at J-PARC...
Thank you!

どうも ありがとう