First experimental determination of the one-proton induced non-mesonic weak decay width for p-shell $\Lambda$-hypernuclei

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on behalf of the FINUDA Collaboration
**Outline**

- The FINUDA experiment @ INFN/LNF DAΦNE

- A revisited analysis of the proton spectra from NMWD of Λ–hypernuclei

- First determination of $\Gamma_p/\Gamma_\Lambda$ for 8 Λ–hypernuclei ($A = 5 - 16$)

- A look to the future
**FINUDA in a nutshell**

- **Energy:** 510 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
- **Part./bunch:** $8.9 \times 10^{10}$
- **Current/ring:** 5.2 A (max)

**Reactions:**

- $e^- + e^+ \rightarrow \phi \rightarrow K^- K^+$
- $K^-_{stop} + {}^A Z \rightarrow {}^{\Lambda A} Z + \pi^-$

**Diagrams:**

- FINUDA interaction/target region
- Superconducting coil
- Compensating magnets
- LMDC
- Beam pipe
- TOFONE
- Clepsydra
- End cap
- Target region
- Beam pipe
- OSIM
- Be window
- Targets
- ISIM
- Tofino

**Equations:**

- $A Z \rightarrow {}^A (Z + 1) + \pi^-$
- $({}^{A-2} Z - 1) + p + n$
- $({}^{A-3} Z - 1) + p + n + n$
FINUDA key features

- very thin nuclear targets (0.1 ÷ 0.3 g/cm²)
- high resolution spectroscopy
- coincidence measurements with large acceptance (2π 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
- systematics on $A$
Physics output \((S = -1)\)

- **nuclear models**
- **4B weak interaction**
- **spectroscopy**
- **(weak) decay**
- **medium effect**
- **quark substructures**
- **low-energy \(N-Y\) interaction**
- **neutron-rich \(\Lambda\)-hypernuclei**
- **deeply bound \(\bar{K}\) states**

M. Agnello et al., PLB 640 (2006) 145
M. Agnello et al., PRL 108 (2012) 042501
M. Agnello et al., NPA 881 (2012) 269
M. Agnello et al., PRC 86 (2012) 057301

M. Agnello et al., PLB 622 (2005) 35
M. Agnello et al., PLB 681 (2009) 139
M. Agnello et al., NPA 835 (2010) 414
M. Agnello et al., PLB 698 (2011) 219

M. Agnello et al., PLB 681 (2009) 151
M. Agnello et al., PLB 681 (2009) 139
M. Agnello et al., NPA 835 (2010) 439
M. Agnello et al., PLB 685 (2010) 247
M. Agnello et al., PLB 701 (2011) 556
M. Agnello et al., NPA 881 (2012) 322

**possible thanks to apparatus performance and stability**
Anatomy of NMWD $p$ spectra

$p$ spectra background subtracted and acceptance corrected

$^{4}\text{He}$, $^{6}\text{Li}$, $^{9}\text{Be}$, $^{10}\text{B}$

$^{12}\text{C}$, $^{13}\text{C}$, $^{15}\text{N}$, $^{16}\text{O}$

$1\omega N$, $2\omega N$, FSI!!!

15 MeV threshold!

common features:
- low energy rise
- structure at $\sim 80$ MeV


FSI and $2\pi$ induced non-mesonic decay

$p$ spectra background subtracted and acceptance corrected


**Revised 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
Refined determination of $\Gamma_{2\alpha}/\Gamma_{NMWD}$

The values of $\mu$ were used to divide the full area of the proton spectra into two regions, $A_{low}$ and $A_{high}$.

It was shown that from the expression:

$$R_1(A) = \frac{A_{low}(A)}{A_{low}(A) + A_{high}(A)}$$

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

It was found:

$$\Gamma_{2\alpha}/\Gamma_p = 0.43 \pm 0.25 \quad (\Gamma_{2\alpha}/\Gamma_{NMWD} = 0.24 \pm 0.10)$$

With the new values we find:

$$\Gamma_{2\alpha}/\Gamma_p = 0.50 \pm 0.24 \quad (\Gamma_{2\alpha}/\Gamma_{NMWD} = 0.25 \pm 0.12)$$

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

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

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

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

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

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

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

fully compatible with the previous one, within the errors.

M. Kim et al., PRL 103 (2009) 182502: 0.29 ± 0.13.

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

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**

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

where $\alpha$ accounts for FSI:

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

$\Gamma_p / \Gamma_\Lambda(5\text{He}_\Lambda) = 0.22 \pm 0.03$

$\Gamma_p / \Gamma_\Lambda(12\text{C}_\Lambda) = 0.49 \pm 0.06$

$\alpha_5(5\text{He}_\Lambda) = 1.15 \pm 0.26$

$\alpha_5(12\text{C}_\Lambda) = 1.04 \pm 0.19$

$\alpha_12(12\text{C}_\Lambda) = 2.48 \pm 0.46$

$\alpha_12(5\text{He}_\Lambda) = 2.77 \pm 0.63$

$\overline{\alpha_5} = 1.08 \pm 0.16$

$\frac{\alpha_5}{\alpha_12} = 2.58 \pm 0.37$

$\alpha(A) = (0.215 \pm 0.031) \cdot A$

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J.J. Szymansky et al., PRC 43 (1991) 849: 0.21 ± 0.07

H. Noumi et al., PRC 52 (1995) 2936: 0.31 ± 0.07

H. Bhang et al., JKPS 59 (2011) 1461: 0.45 ± 0.10

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*input: experimental results only*

*no INC calculation*

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**assumption**

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

- H. Bhang et al., JKPS 59 (2011) 1461.
- M. Agnello et al., PLB 681 (2009) 139.
J-PARC K1.1 beam line

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

<table>
<thead>
<tr>
<th>Beam line</th>
<th>K1.8</th>
<th>K1.8BR</th>
<th>K1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum</td>
<td>1.5 GeV/c</td>
<td>1.1 GeV/c</td>
<td>1.1 GeV/c</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>$0.5 \times 10^6$/spill</td>
<td>$1.2 \times 10^6$/spill</td>
<td>$1.0 \times 10^6$/spill</td>
</tr>
<tr>
<td>$\frac{d\sigma}{d\Omega} (^{7}\text{Li}(3/2^+, \theta = 10^\circ))$</td>
<td>7.1$\mu$b/sr</td>
<td>5.7$\mu$b/sr</td>
<td>4.8$\mu$b/sr</td>
</tr>
<tr>
<td>Relative $\gamma$-ray yield</td>
<td>1</td>
<td>5.7</td>
<td>4.8</td>
</tr>
<tr>
<td>$K/\pi$ ratio</td>
<td>&lt; 0.9</td>
<td>~3</td>
<td></td>
</tr>
<tr>
<td>$\gamma$-ray peak broadening</td>
<td>8.2%</td>
<td>6.1%</td>
<td></td>
</tr>
</tbody>
</table>

old (2008) conservative (?) perspective

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

Cylindrical Detector System

(K1.8BR spectrometer)

essential requirements

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

unavoidably biased by the FINUDA experience

SKS magnet

(K1.8 spectrometer)
A possible apparatus concept layout

- **π⁺** beam enters the apparatus concept layout.
- **7Li** targets are used along with other elements: 9Be, 12C, 16O, 5He, 9Be, 11B, 12C, 15N, and 16O.
- **Target thickness:**
  - 0.7 gr/cm²
  - 1.0 gr/cm² along the beam.
- The layout includes a magnet, CDC (Cherenkov Detector Chamber), and CDH (Cherenkov Detector Hodoscope) chambers.
- Additional elements include a beam position chamber, kaon decay veto, and beam line tracker.
Expected rates (rough estimate)

- Educated guess
  - Interspill: 3.5 s
- From previous experience
  - KEK-PS: E336, E369, E419, E462, E508
  - Formation rate on 1 g/cm² target
    - $\sim 1 \, ^{12}\text{C}_\Lambda \text{ g.s.} / 10^8 \pi^+$
- B.R. (0.5), $\Delta \Omega$ (0.5), $\varepsilon_{\text{riv/rec}}$ (0.5)

- $\sim 10^8 \pi^+ / \text{spill}$
- $\sim 10^{12} \pi^+ / \text{day}$
- $\sim 10^4 \, ^{12}\text{C}_\Lambda \text{ g.s.} / \text{day}$
- $\sim 10^3 \, ^{12}\text{C}_\Lambda \text{ g.s.} / \text{day}$

- From previous experience

- $\sim 10^3 \pi^+ / \text{spill}$
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

Waiting for J-PARC scientific program restart...