FINUDA: Hypernuclear Factory

- The FINUDA experiment
  - the physics program
  - the apparatus
  - next data taking

- The scientific results
  - hypernuclear spectroscopy
  - hypernuclear decays
  - search for neutron-rich hypernuclei
  - Sigma-hypernuclei
  - Kaon deeply-bound nuclear states

Paola Gianotti For the FINUDA collaboration
The FINUDA Collaboration

- Bari University and I.N.F.N. Bari
- Brescia University and I.N.F.N. Pavia
- KEK
- L.N.F. / I.N.F.N. Frascati
- Pavia University and I.N.F.N. Pavia
- RIKEN
- Seoul National University
- Teheran Shahid Beheshty University
- Torino University and I.N.F.N. Torino
- Torino Polytechnic and I.N.F.N. Torino
- Trieste University and I.N.F.N. Trieste
- TRIUMF
**FINUDA @ DAΦNE**

- **Energy**: 510 MeV
- **Luminosity**: \(5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\)
- **\(\sigma_x\) (rms)**: 2.11 mm
- **\(\sigma_y\) (rms)**: 0.021 mm
- **\(\sigma_z\) (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)

**Equation**:

\[ e^- + e^+ \rightarrow \phi \rightarrow K^- K^+ \]

\[ K^-_{\text{stop}} + {}^A Z \rightarrow {}_\Lambda {}^A Z + \pi^- \]

\[ {}^A Z \rightarrow {}^{(A-2)}(Z-1) + p + n \]

\[ {}^{(A-2)} Z + n + n \]
FINUDA @ DAΦNE
FINUDA @ DAΦNE
**FINUDA detectors performances**

- **s.c. solenoid:** $B = 1.0 \, \text{T}$; field homogeneity within 2%
- **interaction/target region:** $K^+/K^-$ identification, hypernucleus production and detection
- **tracking devices:** measurement of trajectories and momenta of charged particles ($\Delta p/p \approx 5\%$)
- **external scintillator barrel:** trigger and neutron detection
- **He chamber:** minimization of particle multiple scattering

**Performance Details:**
- $\Delta p/p$: He atmosphere = 5\%
- $\Delta p/p$: air = 2\%
- $\sigma_z = 30 \, \mu\text{m}$; $\Delta E = 25\%$ FWHM (K)
- $\sigma_t = 250 \, \text{ps}$
- $\sigma(\rho, \phi) = 150 \, \mu\text{m}$; $\sigma_z \leq 1\%$ wire length
- $\sigma(\rho, \phi) = 150 \, \mu\text{m}$; $\sigma_z = 500 \, \mu\text{m}$
- $\text{efficiency} \geq 10\%$; $\Delta E = 8 \, \text{MeV}$
- $\sigma_t = 500 \, \text{ps}$ FWHM
- $\sigma_z \leq 1\%$ wire length
- $\sigma_z = 500 \, \mu\text{m}$
**FINUDA key features**

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

- Coincidence measurement with large acceptance
  - Decay mode study

- Different targets in the same run
  - High degree of flexibility
FINUDA first data taking

14-Oct-2003 to 22-Mar-2004:

250 pb⁻¹ delivered to FINUDA

- 33 pb⁻¹ machine tuning
- 10 pb⁻¹ FINUDA debug
- 190 pb⁻¹ useful data taking
Luminosity monitor
Bhabha events

Bhabha trigger:
- 2 hits on tofino below threshold
- back to back topology
- multiplicity (=2) on tofone
- Time correlation tofino-tofone (<10ns)
**K⁺/K⁻ identification**

Hypernuclear trigger:
- 2 hits on tofino over threshold (kaon)
- extended back to back
- multiplicity (>2) on tofone
- Time correlation tofino-tofone (<10ns)

only two measured points on ISIM

very effective slow kaon recognition

K stop calculation GEANE tracking

Kaon thr.

over threshold
The nominal momentum of $K^\pm$ is 127 MeV/c for a $\Phi$ produced at rest.

By evaluating the total momentum of $e^+e^-$ we can determine $\Phi$ momentum.
$K^+ / K^-$ stopping points

Due to the beam-crossing angle 12.5 mrad the $\Phi$ is produced in flight and the kaons do not have all the same momentum.
Hypernuclear spectroscopy

Hypernuclei are produced following Φ decay via strangeness exchange reaction

\[ \Phi \rightarrow K^+ K^- \quad (49\%) \]

\[ \downarrow K^- + A Z \rightarrow \Lambda Z + \pi^- \quad (\sim 10^{-3}) \]

FINUDA, being a high acceptance magnetic spectrometer, can detect all the particles produced and following \( K^- \) interaction with the target.

Not only hypernuclear systems can be studied.
The hypernuclear event

\[ \pi^- \mu^+ \mu^+ K^+ K^- \pi^- \Phi \]
**Momentum resolution**

FINUDA is a composite detector ⇒ alignment procedure is crucial

- straight cosmic rays, collected during and after data taking, are used
- Iterative procedure

\[ \Delta p/p \sim 0.5\% \]

\[ K^+ \rightarrow \pi^+\pi^0 \]

\[ K^+ \rightarrow \mu^+\nu_\mu \]
\[ K^- + ^{12}\text{C} \rightarrow ^{12}\Lambda\text{C} + \pi^- \]

Raw spectrum of negative pions coming out the $^{12}\text{C}$ targets. Hypernuclear peaks are visible already without any background subtraction.
Background reactions: $\pi^-$ spectrum

$$K^- p \rightarrow \Sigma^+ \pi^-$$

$$K^- n \rightarrow \Sigma^0 \pi^-$$

$$K^- n \rightarrow \Lambda \pi^-$$

$$K^- n \rightarrow \Sigma^- \pi^0$$

$$\Sigma^- \rightarrow n \pi^-$$

$$K^- (NN) \rightarrow \Sigma^- N$$

$$\Sigma^- \rightarrow n \pi^-$$

Apparatus cut for 4 points tracks
FINUDA vs. KEK-E369

$^{12}\text{C}(K^-_\text{stop},\pi)^{12}\text{C}$

$\Delta E \sim 1.3$ MeV FWHM

$^{12}\text{C}(K^+,\pi^+)^{12}\text{C}$

$\Delta E \sim 1.5$ MeV FWHM


$^{12}\text{C}$ excitation spectrum

$\text{Excitation Energy } Ex = B_\Lambda - B_\Lambda \text{ g.s.}$

FINUDA fit with 7 peaks is more precise (better $\chi^2$) and more similar to theoretical calculation.
7Li Spectroscopy

**Signal Fit Results**

- $\chi^2$/d.o.f. $\approx 1.2$
- $\sigma = 0.54$ MeV (fixed)

### Target 4: Binding Energy

- $K^- + n \rightarrow \Lambda + \pi^-$
- $K^- + (np) \rightarrow \Sigma^- + p$ (negligible)

- $\mu_1 = -5.38 \pm 0.15$ MeV $Y_1 = 55 \pm 2$
- syst. $\approx 0.18$ MeV $\Delta = 1.69$ MeV
- $\mu_2 = -3.69 \pm 0.17$ MeV $Y_2 = 50 \pm 12$

The result is steady when varying binning, (size and limits) and fit interval.

---

**Bonomi Talk**

“bound state” -5.58±0.03 MeV Juric et al., NPB 52 (1973) 1
Vanadium spectroscopy

$^{51}$V spectrum measured by KEK E369 experiment via $(\pi^+, K^+)$ associate production
Vanadium spectroscopy

FINUDA spectrum with background reactions superimposed

With respect to \((\pi^+, K^+)\) reaction, \((K^-, \pi^-)\) can access only excited states
Aluminum spectroscopy

The only available data have poor resolution

Background subtracted
Capture rates

Hypernuclear capture rate/$K_{\text{stop}}^{-}$ (integrated over the bound region) as a function of the mass number.

Available data are not enough to perform spectroscopic studies, but we can evaluate capture rate as a function of the mass number.
In medium-heavy hypernuclei mesonic decays ($\Lambda \rightarrow p \pi^-$; $\Lambda \rightarrow n \pi^0$) are suppressed due to Pauli blocking. Non-mesonic weak interaction ($\Lambda p \rightarrow n p$; $\Lambda n \rightarrow n n$) are then more favored.
Theoretical calculation of Ep without (top) and with (bottom) FSI effects. Data are from KEK-E508.

Proton energy spectra in coincidence with a $\pi^-$ from hypernucleus formation.

Thanks to its thin targets FINUDA has reduced the Ep low energy threshold. Spectrum shape at 20-40MeV is important for evaluating FSI contribution.
Hypernuclear rare decay

\[ K^- + {}^6\text{Li} \rightarrow \pi^- + \begin{cases} 
\Lambda^5\text{He} + p \\
\Lambda^4\text{He} + p + n \\
\Lambda^4\text{H} + p + p 
\end{cases} \]

\[ \begin{array}{c}
\text{Hyper-fragments} \\
\text{production}
\end{array} \]

\[ d + d \]

\[ p + t \]

\[ d + p + n \]

\[ p_d = 570 \text{ MeV/c} \]

back to back topology

\[ \text{FINUDA Exp.} \]

Run n.:
Event n.:
Date: 04/
Neutron-rich hypernuclei

Hypernuclei with a large neutron excess have been theoretically predicted (L. Majling, NPA 585 (1995) 211c).

The Pauli principle does not apply to the $\Lambda$ inside the nucleus + extra binding energy ($\Lambda$ "glue-like" role) $\Rightarrow$ a larger number of neutrons can be bound with respect to ordinary nuclei.

- **Hypernuclear physics:**
  $\Lambda$N interactions at low densities, the role of 3-body forces
- **Neutron drip-line:**
  response of neutron halo on embedding of $\Lambda$ hyperon, hypernuclear species with unstable nuclear core
- **Astrophysics:**
  Feedback with the astrophysics field: phenomena related to high-density nuclear matter in neutron stars.
Neutron-rich hypernuclei

Two production mechanisms:

1) strangeness + double charge exchange

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

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

2) strangeness exchange with \( \Lambda-\Sigma \) coupling

\[ K^- + p \rightarrow \Sigma^- + \pi^+ \]
\[ \rightarrow \Sigma^- + p \rightarrow \Lambda + n \]

\[ \pi^- + p \rightarrow \Sigma^- + K^+ \]
\[ \rightarrow \Sigma^- + p \rightarrow \Lambda + n \]
neutron-rich hypernuclei

$$K^- + ^6Li \rightarrow \ ^6\Lambda H + \pi^+ \ (N/Z = 5) \ \text{NEW}$$

$$K^- + ^7Li \rightarrow \ ^7\Lambda H + \pi^+ \ (N/Z = 6) \ \text{NEW}$$

$$K^- + ^{12}C \rightarrow \ ^{12}\Lambda Be + \pi^+ \ (N/Z = 2)$$

From literature FINUDA value 90% C.L.

<table>
<thead>
<tr>
<th>System</th>
<th>FINUDA value 90% C.L.</th>
<th>From literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\Lambda H$</td>
<td>$\pm 0.4^{+0.4}_{-0.4} \text{stat-0.1 syst}\cdot 10^{-5}/K^- \text{stop}$</td>
<td>-</td>
</tr>
<tr>
<td>$^7\Lambda H$</td>
<td>$\pm 0.9^{+0.4}_{-0.4} \text{stat-0.1 syst}\cdot 10^{-5}/K^- \text{stop}$</td>
<td>-</td>
</tr>
<tr>
<td>$^{12}\Lambda Be$</td>
<td>$(2.0 \pm 0.4^{+0.3}_{-0.4} \text{stat-0.1 syst})\cdot 10^{-5}/K^- \text{stop}$</td>
<td>$6.1\cdot 10^{-5}/K^- \text{stop}$</td>
</tr>
</tbody>
</table>

More details

B. Dalena Poster

PLB 640 (2006) 145
**Sigma hypernuclei**

The strong $\Sigma N \rightarrow \Lambda N$ conversion reaction in nuclear matter is broad as few tens of MeV. To detect a $\Sigma$-bound state, the $\Sigma$ width must be less than the separation between two adjacent $\Sigma$ hypernuclear levels.

FINUDA can detect the formation and decay of $\Sigma$-hypernuclei via $(K^{-}_{\text{stop}}, \Sigma \pi)$

\[
K^{-}_{\text{stop}} + A \rightarrow \Sigma B + \pi^{\pm}_{\text{prompt}} \\
\Sigma + N \rightarrow \Lambda + N
\]

The momentum of the $\pi^\pm$ produced with the $\Sigma$ is between 150 - 200 MeV/c. To increase acceptance lower resolutions tracks are used.

The $\Lambda$ is reconstructed via its decay products.
$^{12}$C Sigma hypernuclei

Monte Carlo simulations of background reactions for $^{12}$C

More details
N. Grion Talk

$K^{-} n \rightarrow \Sigma^{0} \pi^{+}$
$\Sigma^{0} \rightarrow n \pi^{+}$

$K^{-} p \rightarrow \Sigma^{+} \pi^{-}$
$\Sigma^{-} \rightarrow p \pi^{-}$

$K^{-} p \rightarrow \Sigma^{+} \pi^{-}$

$K^{-} n \rightarrow \Lambda \pi^{-}$

$K^{-} (NN) \rightarrow \Sigma^{+} N$
$\Sigma^{-} \rightarrow n \pi^{-}$

Diagram showing various reactions and distributions of particles with momentum in MeV/c.
Deeply Bound Kaonic States

- Akaishi-Yamazaki
- Weise et al.
- Gal et al.
- Oset, Ramos et al.
- Wycech et al.
- Schäffner-Bielich et al.

Deep potentials → large B.E.
     small widths
     a few nucleon aggregate

Shallow potentials → moderate-large B.E.
     large widths (>50 MeV),
     more visible on heavy systems

EXP. SITUATION
Scarce information

Missing mass

Invariant mass

FINUDA results
A. Filippi Talk
S. Piano Talk
Fujioka Poster

KEK, AGS, FINUDA

FINUDA, FOPI
Targets’ setup for next data-taking

- **Choice:** 2x $^6$Li, 2x $^7$Li, 1x $^9$Be, 1x $^13$C
- **We focused on medium-light targets to allow a wider spectrum of analyses**
  - Hypernucelar spectroscopy
  - Hypernuclei decay modes
  - Bound kaonic states
  - Rare hypernuclear decay

Target’s thickness evaluated taking into account the narrower (1.8 mm) TOFINO:
- $^7$Li, $^6$Li as in the previous run (+cover)
- $^9$Be: 2 mm
- $^9$Be: 3 mm + cover (e.g. 100 µm mylar)
### NMWD: yield estimation for next data taking (1 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Target</th>
<th>np $(\pi$ coinc.)</th>
<th>nn $(\pi$ coinc.)</th>
<th>nnp/nnn $(\pi$ coinc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$Li (2T)</td>
<td>1200</td>
<td>800</td>
<td>120/80</td>
</tr>
<tr>
<td>$^7$Li (2T)</td>
<td>1200</td>
<td>800</td>
<td>120/80</td>
</tr>
<tr>
<td>$^9$Be (2T)</td>
<td>800</td>
<td>600</td>
<td>80/60</td>
</tr>
<tr>
<td>$^{13}$C (1T)</td>
<td>300</td>
<td>200</td>
<td>no</td>
</tr>
<tr>
<td>$^{16}$O(1T)</td>
<td>300</td>
<td>200</td>
<td>no</td>
</tr>
</tbody>
</table>

- Such statistics are adequate to improve our analyses on
  - Neutron Rich Hypernuclei
  - Spectroscopy of p-shell Hypernuclei
  - Mesonic decays
# Expected events for NRH

<table>
<thead>
<tr>
<th>Hypernucleus</th>
<th>Target</th>
<th>$B_\Lambda$ (MeV)</th>
<th>$p_\pi$ (MeV/c)</th>
<th>Production rate / $k_{\text{stop}}$</th>
<th>Events</th>
<th>U.L. 90% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\Lambda H$</td>
<td>$^6\text{Li}$</td>
<td>4.1$^{[1]}$</td>
<td>252</td>
<td>&lt; 2.5 $\times$ 10^{-5}$^{[3]}$</td>
<td>430</td>
<td>$6.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^7\Lambda H$</td>
<td>$^7\text{Li}$</td>
<td>5.2$^{[2]}$</td>
<td>245</td>
<td>&lt; 4.5 $\times$ 10^{-5}$^{[3]}$</td>
<td>460</td>
<td>$6.9 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^9\Lambda \text{He}$</td>
<td>$^9\text{Be}$</td>
<td>8.5$^{[2]}$</td>
<td>257</td>
<td>&lt; 2.3 $\times$ 10^{-4}$^{[4]}$</td>
<td>600</td>
<td>$6.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{13}\Lambda \text{Be}$</td>
<td>$^{13}\text{C}$</td>
<td>11.7$^{[2]}$</td>
<td>259</td>
<td>(?)</td>
<td>100</td>
<td>$1.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{16}\Lambda \text{C}$</td>
<td>$^{16}\text{O}$</td>
<td>7.3(2$^+$)$^{[5]}$</td>
<td>264</td>
<td>&lt; 6.2 $\times$ 10^{-5} (0$^+$)$^{[4]}$</td>
<td>200</td>
<td>$8.2 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.6(0$^+$)$^{[2]}$</td>
<td>271</td>
<td>6 $\times$ 10^{-8} (2$^+$)$^{[5]}$</td>
<td>190</td>
<td>$8.5 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Summary

Data analysis of first data taking period carried out successfully (30 \times 10^6 events on tape)

Results on spectroscopy are competitive with world published data

Observation of K^- -Nucleons bound states

Upper limit for the NRH production:

- better than published for $\Lambda^{12}Be$
- measured for the first time for $\Lambda^6H$ and $\Lambda^7H$

Hints on NMWD possibilities and other rare decays
Future plans

New data-taking starting now ($\sim 1\text{fb}^{-1} \rightarrow $ statistics x 5) focused on light-medium targets ($^6\text{Li}$, $^7\text{Li}$, $^9\text{Be}$, $^{16}\text{O}$)

New internal TOF system (KEK) to improve Trigger capabilities

Increased DAQ rate by a factor 4 to stand higher DAΦNE luminosity

Improvement of the reconstruction program

- geometrical alignment
- detector calibration
- pattern recognition strategy
- selection criteria