Future Hypernuclear Program at Hall A

F. Garibaldi-INFN Roma-gr. Coll. Sanita'

- Physics
- Experimental challenge
  - Forward angle - Septum magnets
  - Energy Resolution
  - PID : the RICH
- Targets, expected rates
- Conclusions
Create a laboratory to study $\Lambda - N$ interaction

Extension of $N-N$ physics to $S \neq 0$ systems

Spectroscopy of hypernuclear physics
- $\Lambda, \Sigma$ (?) coexist with nucleons,
- deeply bound hyperon (Pauli princ. work?)

Non-mesonic weak decays of hypernuclei
($\Delta I = 1/2$ rule, strength of $\Lambda p \rightarrow np$ vs $\Lambda n \rightarrow nn$)

Bound state of $\Sigma$ hypernuclei ??
(see ref. PRL 80 (1998) 1605)

Main experimental goals

Energy levels, splittings
cross sections
weak decays
(polarizations)
Strange baryons may appear in neutral $\beta$-stable matter through processes like

$$n + e^- \rightarrow \Sigma^- + \nu_e$$

as soon as the chemical potentials are such that

$$\mu_n + \mu_e > M_{\Sigma^-}$$

The presence of strange baryons in neutron stars strongly affects their properties.

Example: mass-central density relation for a nonrotating (left) and rotating (right) star

There is growing evidence that hyperons appears the first of the strange hadrons in neutron starts at around twice normal density....The onset of the hyperon formation is controlled by the attractive hyperon-nucleon interaction which can be extracted from hypernucleon scattering data and hypernuclear data (J. Shaffner-Bielich et al: Hyperstars: Phase Transition to (meta)-Stable Hyperonic matter in neutron Stars, arXiv: astro-ph/0005490)

Additional experimental data from hypernuclei will be useful in establishing the foundations of high density matter models. This is especially relevant for the hyperon-nucleon interactions, for which relevant systems are more likely to be produced in current accelerators than for hyperon-hyperon interactions", in S. Balberg et al: Roles of hyperons in Neutron Stars, arXiv: astro-ph/9810361

The effect strongly depends upon the poorly known interactions of strange baryons.

More data needed to constrain theoretical models.
Precision Λ hypernuclear spectroscopy

Hypernuclear structure vs ΛN interaction

- Hypernuclear data well described by weak coupling model

Λ (s-shell) + JΛ-1 → J = JΛ-1 ± 1/2
(A hyperon) (parent nucleus) (created doublet state) (J state)

- Many particle shell model:

| s^4 p^A-5 \cdot s\Lambda; J\text{T} > configurations |

- Hypernuclear Hamiltonian:

\[ H = H_N + h_\Lambda + H_{\Lambda N} \]

\( H_N \) = hamiltonian for the NUCLEAR CORE
\( h_\Lambda \) = Kinetic term for the hyperon
\( H_{\Lambda N} = \sum_{i=1}^{A-1} V_{\Lambda N} (\vec{r}_i - \vec{r}_\Lambda) \) Residual ΛN interaction

\[ V_{\Lambda N} = V_0(r) + V_\sigma(r) \sigma_N \cdot \sigma_\Lambda + V_{\lambda N}(r) \lambda_\Lambda \cdot \sigma_N + V_{\lambda N}(r) \lambda_\Lambda \cdot \sigma_N + V_T(r) S_{12} \]

(\( S_{12} = 3(\sigma_N \cdot r)(\sigma_\Lambda \cdot r) - \sigma_N \cdot \sigma_\Lambda \))

\( V_{\text{central}} \)
\( \Delta \text{ (spin-spin)} \)
\( \sigma_\Lambda \text{ (spin-orbit)} \)
\( \sigma_N \text{ (spin-orbit)} \)
\( T \text{ (tensor)} \)

- Doublet splitting determined mainly by \( \Delta, \sigma_\Lambda, T \)

(\( \sigma_N \) affect the spacing between doublets)

\[
\begin{array}{c|c|c|c|c}
\text{MeV} & 8\text{Li} & 9\text{Li}_\Lambda \\
\hline
4 & 1^+ & 7/2^+ \\
3 & 3^+ & 7/2^+ \\
2 & 5/2^+ & 5/2^+ & 3/2^+ \\
1 & 1^+ & 1/2^+ \\
0 & 2^+ & 3/2^+ & 3/2^+ & 5/2^+ & 3/2^+
\end{array}
\]

Canonical Standard FMZE YNG
\[ ^{12}\text{C}(\pi^+,K^+)^{12}\text{C}_\Lambda \] data taken from M.Akei et al., NP A534 (1991) 478

Energy resolution 4 MeV

More recent KEK data
INS-Rep.-1037, Univ. of Tokyo, 1994

Energy resolution 2 MeV

\[ ^{12}\text{C}(e,e')^{12}\text{B}_\Lambda \] 

Energy resolution 350 keV

--- new aspects of hypernuclear structure

* production of hypernuclei not available otherwise \((^7\text{He}_\Lambda, ^9\text{Li}_\Lambda)\)

* energy resolution = 350 keV
Hall A - Two High Resolution Spectrometers

QDQ - Momentum Range: 0.3 - 4 GeV/c  \( \Delta p/p : 1 \times 10^{-4} - \Delta p = \pm 5\% - \Delta \Omega = 5 - 6 \text{ mr} \)
E-94-107 - High Resolution 1p shell Hypernuclear Spectroscopy

F. Garibaldi, S. Frullani, J. LeRose, P. Markowitz, T. Saito

Cross section VS. angles

\[ {^9\text{Be}(e,e'K)^9\text{Li}_\Lambda} \]

very good energy resolution
forward angle reasonable counting rates
very good PID unambiguous kaon identification

E\(_1\) = 4 GeV
\(\omega = E_\gamma \sim 2.2\) GeV
\(p_k = 1.9\) GeV
\(\theta_e = \theta_k = 6^\circ\)

\(Q^2 = 0.0789\) Gev\(^2\)
**Energy Resolution**

1. $\Delta E/E : 2.5 \times 10^{-5}$
2. $\Delta P/P$ (HRS + septum) $\sim 10^{-4}$
3. Straggling, energy loss...

**Forward angle - Septum magnets**

- Meet the requirements of the 94-107 and all “possible” experiments in Hall A
  - Small scattering angle ($12.5 \rightarrow 6$)
  - No degradation in HRS performances
  - General purpose device
    - Continuous covering scattering angles ($6 \rightarrow 12.5$)
    - Two independent arms
<table>
<thead>
<tr>
<th>Length</th>
<th>88 cm</th>
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<tbody>
<tr>
<td>Magnetic length</td>
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<tr>
<td>Height of the gap</td>
<td>25 cm</td>
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<tr>
<td>Width of the gap</td>
<td>10.4 cm</td>
</tr>
<tr>
<td>central edge</td>
<td></td>
</tr>
<tr>
<td>Width of the gap</td>
<td>18.4 cm</td>
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<tr>
<td>exit edge</td>
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<tr>
<td>Angular acceptance</td>
<td>4.7 mr</td>
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<table>
<thead>
<tr>
<th>p (GeV)</th>
<th>θ (degrees)</th>
<th>β (degrees)</th>
<th>R (cm)</th>
<th>∫B.dl (Tesla.m)</th>
<th>B0 (Tesla)</th>
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<td>6.5</td>
<td>740.8</td>
<td>0.76</td>
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<td>12.5</td>
<td>11.9</td>
<td>404.6</td>
<td>1.39</td>
<td>1.65</td>
</tr>
<tr>
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<td>6</td>
<td>6.5</td>
<td>740.8</td>
<td>1.51</td>
<td>1.8</td>
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<tr>
<td>4</td>
<td>12.5</td>
<td>11.9</td>
<td>4046</td>
<td>2.77</td>
<td>3.3</td>
</tr>
</tbody>
</table>
I period

sieve slit

II period

Y target

non optimized

optimized
The PID Challenge

Very forward angle ---> high background of $\pi$ and p
-TOF and 2 aerogel in not sufficient for unambiguous K identification!

Kaon Identification through Aerogels:

$\text{KAONS} = AERO1 \cdot AERO2$

Hypernuclei -> smaller scattering angle
-> higher background --> something else is needed
Figure 2: $^{16}O(e,e'K)^{16}N_1$ reaction. (a) Timing spectrum: solid lines set a cut for events “IN the kaon peak”, dashed lines select events “OFF the peak” used for subtraction. (b) Missing Mass spectrum for all the events entering spectrum (a). (c) Missing Mass spectrum for events “IN the peak”.

Figure 5: Same as fig 3 for the $^9Be(e,e'K)^9Li_A$ reaction.
Contamination of pion and proton on the K signal with different PID systems, for the counting rates of two levels (10^{-2} Hz and 10^{-4} Hz)

<table>
<thead>
<tr>
<th>Process</th>
<th>Rates</th>
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</thead>
<tbody>
<tr>
<td>signal</td>
<td>10^{-4} – 10^{-2}</td>
</tr>
<tr>
<td>accidentals</td>
<td></td>
</tr>
<tr>
<td>(e,e')(e,pi)</td>
<td>100</td>
</tr>
<tr>
<td>(e,e')(e,p)</td>
<td>100</td>
</tr>
<tr>
<td>(e,e')(e,k)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Contamination of pion and proton on the K signal with different PID systems, for the counting rates of two levels (10^{-2} Hz and 10^{-4} Hz)
\[ \cos \theta = \frac{1}{n \beta} \]

\[ \Delta \beta / \beta = \tan \Delta \theta \]

\[ N = \text{p.e. per ring} \]

\[ \Delta \theta \rightarrow \Delta \theta / \sqrt{N} \]

- \( n \) fixed by the momentum (2 GeV/c)
- \( C_6 F_{14} \), transparent down to 160 nm
- compact (~ 50 cm)
- relatively thin (18% X0)
- 310 x 1820 mm\(^2\)
- quartz window 5 mm

Like ALICE and STAR RICH

**Ring Imaging CHerenkov Detector**

Detect single photon positions to reconstruct the Cherenkov angle:

- **Optics**
  - Liquid Freon \((C_6F_{14}, n=1.28)\) 15 mm
  - 300 nm
  - Csl film coated on a Pad Plane
  - Multi Wire and Pad Proportional Chamber filled with Methane at STP
- **Position Detector**
  - 11520 analog chs, multiplexed S&H
- **Proximity Focusing**
  - Freon
  - Quartz
  - Drift Electrode
  - MWPC
  - FE Electronics
  - Csi pad Photocathode
N. of detected photoelectrons

\[ N_{p.e.} = 370L \sin^2 \vartheta_c \prod_i \varepsilon_i \Delta E \approx 20 - 50 \]

Angle Reconstruction (Freon=1.4 cm, Gap=10 cm, P=2 GeV/c)

\[ \sigma_{\vartheta} = 2.5 \quad \vartheta_{\text{max}}(\vartheta) = 0.55 \]

\[ \sigma_{\vartheta} = 1.9 \quad \vartheta_{\text{max}}(\vartheta) = 0.65 \]

\[ \sigma_{\vartheta} = 1.7 \quad \vartheta_{\text{max}}(\vartheta) = 0.68 \]

π, K separated by 30 mrad with 3 mrad: 10 \( \sigma \)

Simulation (spectra) done with 6 \( \sigma \)

5 mrad good enough

Separation power

\[ \vartheta_2 - \vartheta_1 = n_\sigma \sigma_{\vartheta_c} \]

Minimize

Maximize

Cherenkov angle resolution

\[ \sigma_{\vartheta_c} = \frac{\sigma_{\vartheta_{p.e.}}}{\sqrt{N_{p.e.}}} \]

Particle mass \( m_1 \), Particle mass \( m_2 \)

Check the # p.e.

Check the single photon ang. res.

(FPP tracking would help)
Many parameters affect the detector performances (\# p.e.)

- quartz transparency in the v.w. region of interest (160 - 220 nm)

- freon purity to not absorb the emitted Cherenkov light
  - freon purity circuit + continuously monitoring

- CsI photocathode
  - evaporation + on line QE absolute measurement
  - QE is strongly affected by oxygen and moisture
    - Careful handling of photocathodes after evaporation
    - Continuous monitoring of gas “purity”
CERN tests
7 GeV/C p beam
Argon CH4 (25/75)
2 photocathodes
Rome and CERN
Equal performances
$N = \sim 12$
Can be extrapolated
to $\sim 14$ with CH4
CERN November 2000

Rome and CERN

Equal performances

\[ N = \sim 12 \]

Can be extrapolated to \sim 14 with CH4

Cosmics Jlab September 2003

\[ A_0 = 30 \]

MIP peak=550

\[ G \sim 8 \times 10^4 \]
Evaporation system

10^{-6} mbar vacuum, 2 nm/s CsI deposition at T = 60 °C (CERN experts indications). Vacuum - heating conditions start 15 - 24 h before evaporation. A post-evaporation heat treatment is done for 12 hours.

Evaporation layout

- PhotoCathode - crucibles plane distance: 42 cm
- 4 μm Ni - 1 μm Au support
- Crucible quantity: 0.8 g weight each one, corresponding to ~ 320 nm thickness (expected and measured)

Expected thickness
Targets
**Kinematics**

\[ E_i = 4 \text{ GeV} \]
\[ \omega = E_\gamma \sim 2.2 \text{ GeV} \]
\[ p_k = 1.9 \text{ GeV} \]
\[ \theta_e = \theta_k = 6^\circ \]
\[ Q^2 = 0.0789 \text{ GeV}^2 \]

**Energy resolution**

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>RESOLUTION</th>
<th>Error FWHM (kev)</th>
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<tbody>
<tr>
<td>beam</td>
<td>(10^{-4}) of 4 GeV (4 (\sigma))</td>
<td>235</td>
</tr>
<tr>
<td>e</td>
<td>(10^{-4}) of 1.8 GeV</td>
<td>180</td>
</tr>
<tr>
<td>k</td>
<td>(10^{-4}) of 1.9 GeV</td>
<td>190</td>
</tr>
<tr>
<td>k stragglng</td>
<td>40 KeV</td>
<td>40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>(\approx 350)</td>
</tr>
</tbody>
</table>

Beam Current: \(i = 100 \mu\text{A}\)

**Counting rates**

<table>
<thead>
<tr>
<th>(^7\text{Li})</th>
<th>(E) (MeV)</th>
<th>(J)</th>
<th>((e,e'K))(\text{nb/GeV}\text{sr}^2)</th>
<th>Rate hr(^{-1})</th>
<th>Error (120 Hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1/2+</td>
<td>0.796</td>
<td>10.2</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>1.59</td>
<td>5/2+</td>
<td>0.181</td>
<td>2.3</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>1.94</td>
<td>3/2+</td>
<td>0.138</td>
<td>1.7</td>
<td>8.2</td>
<td></td>
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<tr>
<td>15.46</td>
<td>3/2-</td>
<td>0.345</td>
<td>4.25</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>17.67</td>
<td>3/2-</td>
<td>1.14</td>
<td>14.6</td>
<td>2.4</td>
<td></td>
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<tr>
<td>(^9\text{Be})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>3/2+</td>
<td>0.179</td>
<td>1.78</td>
<td>8.0</td>
<td></td>
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<tr>
<td>0.69</td>
<td>5/2+</td>
<td>0.975</td>
<td>9.7</td>
<td>3.0</td>
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<tr>
<td>1.42</td>
<td>1/2+</td>
<td>0.196</td>
<td>1.95</td>
<td>7.6</td>
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<tr>
<td>1.71</td>
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<tr>
<td>2.43</td>
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<tr>
<td>2.78</td>
<td>7/2+</td>
<td>0.036</td>
<td>3.04</td>
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<table>
<thead>
<tr>
<th>(^{12}\text{C})</th>
<th>(E) (MeV)</th>
<th>(J)</th>
<th>((e,e'K))(\text{nb/GeV}\text{sr}^2)</th>
<th>Rate hr(^{-1})</th>
<th>Error (120 Hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1-</td>
<td>0.789</td>
<td>5.89</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>0.03</td>
<td>2-</td>
<td>4.57</td>
<td>34.6</td>
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</tr>
<tr>
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<td>0.98</td>
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<tr>
<td>10.03</td>
<td>3+</td>
<td>0.778</td>
<td>5.81</td>
<td>4</td>
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<tr>
<td>10.63</td>
<td>3+</td>
<td>3.58</td>
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<tr>
<td>11.22</td>
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<td>4.6</td>
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</tr>
<tr>
<td>11.93</td>
<td>2+</td>
<td>0.293</td>
<td>2.18</td>
<td>7.3</td>
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<table>
<thead>
<tr>
<th>(^{16}\text{O})</th>
<th>(E) (MeV)</th>
<th>(J)</th>
<th>((e,e'K))(\text{nb/GeV}\text{sr}^2)</th>
<th>Rate hr(^{-1})</th>
<th>Error (120 Hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1-</td>
<td>2.78</td>
<td>20.7</td>
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<tr>
<td>0.44</td>
<td>0-</td>
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<td>1.91</td>
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<tr>
<td>6.89</td>
<td>1-</td>
<td>2.01</td>
<td>15.0</td>
<td>6.6</td>
<td></td>
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<tr>
<td>7.03</td>
<td>2-</td>
<td>5.28</td>
<td>39.4</td>
<td>1.5</td>
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</tr>
</tbody>
</table>

Target thickness = 100 mg/cm\(^2\)
1. $^{12}\text{C}$: comparison with present data, better understanding of the data with hadronic probes (additional peaks found with respect to the predictions).

2. $^9\text{Be}$: spin doublets, $s$-$s$ potential parameter clarification.

3. $^7\text{Li}$: large neutron excess

4. $^{16}\text{O}$: “simple” structure, ground state doublet investigation

$^{52}\text{Cr}$ : due to the stability of $^{51}\text{V}$ core, the level structure should be rather simple. Expectation supported by spectroscopy on $^{51}\text{V}$. Typically the cross section for heavier target are lower. It is observed that this suppression is dependent to $2J+1$. For this reason the cross section for elettroproduction of $^{52}\text{V}_\Lambda$ should be comparable with $^{12}\text{C} \rightarrow ^{12}\text{B}_\Lambda$ or $^9\text{Be} \rightarrow ^9\text{Li}_\Lambda$ cases
Expected spectra for $^{52}$Cr

Calculations (M. Sotona) from Woods-Saxon potential with two different hypotheses:

1. $V_{LS} = 0.4$ MeV, to fit splitting measured in $\gamma$ spectroscopy

Note: this 2-nd widening may be partially attributed to other structure effects.
June 2002 optics tests

(Target (^{12}C): 114 mg/cm^{2})

**Kinematics:**
- \( E_i = 4.7 \text{ GeV} \)
- \( P_e = 3.8 \text{ GeV/c} \)
- \( P_{\text{hadr}} = 1.5 \text{ GeV/c} \)

**Resolution** 720 KeV

with our setup (no windows) and kinematics

\(~ 350 \text{ keV}~\)
Conclusions

- very good energy resolution hypernuclear spectroscopy experiment on 1p shell nuclei will be performed in Hall A

- first septum magnet used for GDH: performances as expected
- second septum being installed
- challenging PID
  - aerogel and RICH performing as expected
- we are ready!