Introduction to Hypernuclear (and Kaon-nucleus) Physics

Outline:
• What is a hypernucleus?
• BB interaction and hypernuclei structure
• Formation of Λ-hypernuclei
• Weak decay of Λ-hypernuclei
• Search for Σ–hypernuclei
• K-N, K-A and Deeply bound kaonic nuclei
• An experimental approach to low-energy kaon physics and some recent results
Hyperons and hypernuclei

• There are six quark flavors in nature: $\begin{bmatrix} u & c & t \\ d & s & b \end{bmatrix}$

$\Lambda = (uds), \Sigma (qqqs), \Xi = (qss), \ldots \rightarrow \text{Hyperons}$

Hyperon = strange baryon ($s \neq 0$); notation: $Y$

Weak decay: $\tau \sim 10^{-10}$ s, $[\Sigma^0 \rightarrow \Lambda \gamma (\sim 10^{-19}$ s)];

$c\tau = \Theta(10 \text{cm})$

| Quark | $I^G$ | $T$ | $S|O|$ | Mass [MeV] |Lifetime [s] | Main Decays |
|-------|------|-----|-------|------------|-------------|-------------|
| $p$   | 1/2+ | 1/2 | 0     | 938.27     | $> 10^{26}$ years | stable     |
| $n$   | 1/2+ | 1/2 | 0     | 939.56     | $887.0 \pm 2.0$ | $p e^- \bar{\nu}_e (100\%)$ |
| $\Lambda$ | 1/2+ | 0   | -1    | 1115.7     | $2.6 \times 10^{-15}$ | $p\pi^- (64.1\%), \pi^0 (35.7\%)$ |
| $\Sigma^+$ | 1/2+ | 1   | -1    | 1189.4     | $0.79 \times 10^{-15}$ | $p\pi^0 (51.8\%), \pi^+ (48.3\%)$ |
| $\Sigma^0$ | 1/2+ | 1   | -1    | 1192.8     | $7.4 \times 10^{-20}$ | $\Lambda \gamma (100\%)$ |
| $\Sigma^-$ | 1/2+ | 1   | -1    | 1197.4     | $1.4 \times 10^{-10}$ | $\pi^- (99.8\%)$ |
| $\Xi^0$ | 1/2+ | 1/2 | -2    | 1314.9     | $2.9 \times 10^{-10}$ | $\Lambda \pi^0 (100\%)$ |
| $\Xi^-$ | 1/2+ | 1/2 | -2    | 1321.8     | $1.6 \times 10^{-10}$ | $\Lambda \pi^- (100\%)$ |
| $\Omega^-$ | 5/2+ | 0   | -3    | 1672.4     | $0.62 \times 10^{-15}$ | $\Lambda K^- (67.8\%), \Xi^- \pi^0 (8.6\%), \Xi^- \pi^- (29.6\%)$ |
| $\Lambda_0^+$ | 1/2+ | 0   | 0     | 6285       | $2.0 \times 10^{-13}$ | $\Lambda \gamma (100\%)$ |
| $\Xi_0^+$ | 1/2+ | 1/2 | -1    | 2446       | $8.5 \times 10^{-13}$ | $\Lambda \pi^0 (100\%)$ |
| $\Xi^0$ | 1/2+ | 1/2 | -1    | 2470       | $1.0 \times 10^{-13}$ | $\Lambda \pi^- (100\%)$ |
| $\Lambda_0$ | 1/2+ | 0   | B=-1  | 5661       | $1.1 \times 10^{-12}$ | $\Lambda \gamma (100\%)$ |
Ordinary baryons are stable: p, n both targets or projectiles (NN, eN, πN…scattering)

But nuclear interaction not limited to the u,d sector…

Since Hyperons have very short lifetime, low energy YN scattering is difficult.

→ extension to strange sector via hypernuclear studies

The First Hypernuclear Event (1953)

P – Cosmic track
A - Nuclear Interaction
B – Hypernuclear Decay at Rest
What is a hypernucleus?

- Normal nucleus: composed of nucleons (proton, neutron)
  At the quark level: p=(uud), n=(udd)
- **Hypernucleus**: not only nucleons but hyperons (one or more) s quarks beside u and d
  - Extension of the strong int. to strange sector
  - Probing the interior of the nucleus
  - Short range strong YN interaction
  - New light on NN interaction
  - A new dimension to world of nuclei: no Pauli p., new symmetries, selection rules,…
  - medium modifications
  - Four fermion weak vertex ($\Lambda N \rightarrow NN$), quark-gluon effects,…
  - Tool to match nuclear and particle physics

  **Knowledge of elementary hyperon-nucleon (YN) and hyperon-hyperon (YY) interaction crucial to fully understand the nuclear force!**
Notation

\[
\begin{align*}
\Lambda & \text{ Total number of baryons (nucleon & hyperon)} \\
Z & \text{ Total charge} \\
\Lambda & \text{ hyperon (other examples -- } \Sigma, \Xi, \ldots) \\
\end{align*}
\]

- Some examples:
  1. \(3p + 3n + 1\Lambda \rightarrow ^7\Lambda\text{Li}\)
  2. \(2p + 2n + 2\Lambda \rightarrow ^6\Lambda\Lambda\text{He}\)
  3. \(1p + 2n + 1\Sigma^+ \\
      2p + 1n + 1\Sigma^0 \\
      3p + 0n + 1\Sigma^- \rightarrow ^4\Sigma\text{He}\)

- Known hypernuclei (strangeness only): \(\Lambda\)-hypernuclei (~50 species), \(\Sigma\)-hypernucleus (only 1), \(\Lambda\Lambda\)-hypernuclei (a few events) and probably one anti-hypernucleus (@RHIC)
Observation of $^3\Lambda H$ and $\overline{^3\Lambda H}$ @ RHIC

- First ever observation of an anti-hypernucleus (4σ signal of $\overline{^3\Lambda H}$)
- The hypertriton and anti-hypertriton signal: 244±35
- The hypertriton and anti-hypertriton lifetime:

\[ \tau = 153 \pm 43 \text{ ps} \]


Gang Wang (UCLA) QM2009
Baryon-Baryon interaction and the structure of hypernuclei

- **GOAL**: unified understanding of NN, YN and YY interactions
- Flavor SU(3) symmetry (symmetry in u, d, s quarks)
- **NN interaction** -- experimentally well known from elastic scattering data
  - phenomenologically well reproduced by meson-exchange (ME) and quark-cluster models (short range repulsion).
- YN, YY interaction: poor scattering data (short lifetime)
  - information from hypernuclei is important
    - (mostly Λ-hypernuclei → ΛN interaction)
In Λ-hypernuclei: No Pauli effect, weak coupling
  - simpler structure
  - extraction of ΛN interaction is rather straightforward

Extension of ME description to strange sector: long history, but not over yet (one, two-ME potentials[Julich, Nijmegen], quark-clusters…)

Some features of the $\Lambda N$ interaction (1)

• $\Lambda N$ and NN One meson exchange models

- Strong vertex
- OME
- $\pi, \rho, \omega, \eta$

Main difference:
- One pion exchange is forbidden ($\Lambda \neq \Lambda \pi$) (Violates isospin symmetry)

OPE forbidden in $\Lambda N$ interaction
→ two $\pi$ exchange dominant
→ $\omega, \eta, 2\rho$ ... allowed

CONSEQUENCES...
Some features of $\Lambda N$ interaction (2)

- weakness of $\Lambda N$ interaction (no OPE)
  e.g., no two body bound state (no hyperdeuteron!)

- $\Lambda N$ is a short range interaction
  two $\pi$, heavier mesons ($K$, $\eta$, $\omega$, $\sigma$, ...) exch.
  quark-gluon picture (manifestation of quark-gluon degrees of freedom?)

Also allowed:

3-body $\Lambda NN$ interaction

3-body forces much less important
In ordinary nuclei ($m_\Delta - m_N \sim 293$ MeV, $m_\Sigma - m_\Lambda \sim 78$ MeV!)

Important to study structure of $\Lambda$-hypernuclei. It is due to the
sizeable $\Lambda N - \Sigma N$ coupling inside nuclear medium (OPE enters at $2$nd order)

More later...
Some features of $\Lambda N$ interaction (3)

**Spin-dependence**

- No experimental data so far from scattering experiments
  -> All information is from hypernuclei
- Data are mostly for light (s- and p-shell) hypernuclei
- Spin dependent terms $\Lambda N$ effective potential in hypernuclei

\[
\begin{align*}
V_\sigma(r) \, \sigma_\Lambda \cdot \sigma_N & \quad \text{.... spin-spin} \\
V_\Lambda(r) \, \sigma_\Lambda \cdot L_{\Lambda N} & \quad \text{.... spin-orbit (}$\Lambda$-spin dependent) \\
V_N(r) \, \sigma_N \cdot L_{\Lambda N} & \quad \text{.... spin-orbit (}$N$-spin dependent) \\
V_T(r) \{3(\sigma_\Lambda \cdot r)(\sigma_N \cdot r)/r^2 - \sigma_\Lambda \cdot \sigma_N\} & \quad \text{.... tensor}
\end{align*}
\]

- $\Lambda$-N **spin-spin** interaction: usually **weak**

  $\sim 0.1\text{MeV}$ for p-shell hyp. (except $^7\text{Li}\text{g.s.)} \rightarrow 0.6\text{MeV}$)

  Some data show that $\Lambda N$ interaction more attractive in spin-singlet (J=0) state than in spin-triplet state (J=1) but situation not clear.
Some features of $\Lambda N$ interaction (4)

$\Lambda$-N **spin-orbit interaction**: small

Note: $\Lambda$-nucleus spin-orbit potential $< 1/10$ N-nucleus potential.

Probably related to **missing** contribution of one body $\pi$ ($\rho$) **exchange** (strong in ordinary nuclei) which suggests that Spin-orbit potential in **ordinary nuclei** mediated by single $\pi$ ($\rho$) exchange.
Spin-dependence

Experiments with high energy resolution essential to study spin dependence

Low-lying levels of $\Lambda$ Hypernuclei

(K$,\pi^-$) or ($\pi^+$,K$^+$)

"Hypernuclear Fine Structure"

split by $\Lambda N$ spin-dependent interactions

$\lesssim$ 0.1 MeV

$\Lambda$, $S_\Lambda$, $T$

Only Ge can separate (~2 keV FWHM)
Hyperons in nuclei

- Y as an impurity
- Influence of the medium on the hyperon:
  Single particle behaviour (mean field) appropriate (although deviations from e.g. 3-body forces, $\Sigma N-\Lambda N$, ...)

- A hyperon influences the nuclear medium: may change some properties of nuclei (size, shape, energy levels ...)

Theoretical prediction:
- A $\Lambda$ makes a loosely-bound light nucleus, such as $^6\text{Li}$, smaller
- $\rightarrow$ glue-like role (Motoba et al., PTP70 (1983) 189)

$$^6\text{Li} + \Lambda \rightarrow ^7\Lambda\text{Li}$$

- Recent experiment gives evidence for such shrinkage $^5\text{He}$ & $^8\text{Be}$ unstable BUT $^6\Lambda\text{He}$ and $^9\Lambda\text{Be}$ stable!!
As in Nuclear Physics, Baryons in the Hypernucleus can be treated as Fundamental Objects.

The Λ maintains its identity in the nuclear medium because the interaction with the nucleus is “weak”.

The Structure is discussed in the particle-hole formalism.

An elementary potential form inserted into the hadronic many-body problem yields a one-body effective potential.

The Λ resides in the 1s shell for the hypernuclear ground state (probes nuclear core!). No Pauli blocking!

General hyperon-nucleus potential

\[ V_{\Lambda N}(r) = V_0(r) + V_\sigma(r) \vec{s}_N \cdot \vec{s}_\Lambda + V_\Lambda(r) \vec{l}_{N\Lambda} \cdot \vec{s}_\Lambda + V_N(r) \vec{l}_{N\Lambda} \cdot \vec{s}_N + V_T(r) S_{12} \]

p shell: 4 radial integrals for p_N, s_Λ w.f.
Overall binding energy of hypernuclei

\[ B_\Lambda (^{A}_{\Lambda}Z) = M (^{A}_{\Lambda}Z) - M (^{A-1}Z) - m_\Lambda \]

- from \( A=3 \) to \( 208 \)
- \( U_\Lambda \sim 27 \text{ MeV} \sim \frac{2}{3} U_N \)
  well reproduces data
  \( \rightarrow \) weakness of \( \Lambda N \) interaction
- **Single particle picture**
  works even for deep states
  unlike for nucleons
- \( \Lambda \) can occupy any single p.
  state: Yg.s. always 1s. \( \rightarrow \) good
  probe of nucleus interior!

(D. J. Millener et al., PRC38 (1988) 2700)
**B_N and B_A very different**

- $B_A$ monotonically increases up to $\sim$27 MeV for $^{208}_\Lambda$Pb ($B_N$ saturates @ $\sim$8MeV ($A \leq 10$))
- $\Lambda$-nucleus mean field depth $\sim$30 MeV (N-nucleus m.f.d. $\sim$50-55 MeV)
- Weakness & smaller range of $\Lambda N$ w.r.t. NN interaction
Test of single-particle states at the center of nucleus

- Hyperons are free from Pauli blocking
  - can stay at the center of the nucleus
  - good probe of nucleus interior
- KEK-PS E369 observed clear and narrow peaks for $s_\Lambda$ and $p_\Lambda$ states of $^{89}\Lambda Y$
  (H. Hotchi et al., PRC64 (2001) 044302)

$\rightarrow$ There are single-particle states in the nuclear interior

Textbook example of single-particle orbits in nucleus
Light hypernuclei (1) --
overbinding problem and charge symm. breaking

• Binding energy of hypernuclei, A=3~5 [exp. Values]

\( ^3_{\Lambda}H \): \( B_{\Lambda} = 0.13 \pm 0.05 \text{ MeV} \) (lightest bound state!)

\( ^4_{\Lambda}H \): \( B_{\Lambda} = 2.04 \pm 0.04 \text{ MeV} \) (ground state, 0\(^+\))
  1.00 \( \pm 0.06 \text{ MeV} \) (excited state, 1\(^+\))

\( ^4_{\Lambda}He \): \( B_{\Lambda} = 2.39 \pm 0.03 \text{ MeV} \) (0\(^+\))
  1.24 \( \pm 0.06 \text{ MeV} \) (1\(^+\))

\( ^5_{\Lambda}He \): \( B_{\Lambda} = 3.12 \pm 0.03 \text{ MeV} \)

• If we use \( \Lambda N \) interaction (centr. pot) which reproduces A=3,4 binding energies, \( ^5_{\Lambda}He \) overbinds by \( \sim 1 \text{ MeV} \) in calculations

\( \rightarrow \) overbinding problem of \( ^5_{\Lambda}He \)

• First pointed out by Dalitz et al. in 1972 \( \text{NPB47 109} \), but not solved for nearly 30 years.
Solution to the overbinding problem? (1)

- **Quark Pauli effect?**
  
  **baryon level**
  
  \[
  \begin{array}{ccc}
  \uparrow & \uparrow & \uparrow \\
  p & n & \Lambda \\
  \end{array}
  \]
  
  no pauli blocking

  **quark level**
  
  \[
  \begin{array}{ccc}
  \uparrow & \uparrow & \uparrow \\
  u & d & s \\
  \end{array}
  \]
  
  partial Pauli blocking

- Is this significant? \(\Rightarrow\) seemingly no
  
Solution to the overbinding problem? (2)

- importance of $\Lambda NN$ three body force

$\Lambda N$-$\Sigma N$ coupling (+ $\frac{5}{4}^{\Lambda}$He structure)
Seems to explain the binding anomaly

$\Lambda NN$ 2$\pi$-exch. component

$\Lambda N$-$\Sigma N$ 2$\pi$-exch. component

Medium-modified $\Lambda N$

$3$-body forces much less important
In ordinary nuclei ($m_\Delta-m_N\sim 293$ MeV, $m_\Sigma-m_\Lambda\sim 78$ MeV!)
Light hypernuclei (2) -- charge symmetry breaking

- \( \Lambda \) has no charge, no isospin
  \( \rightarrow \) **difference of \( \Lambda p \) and \( \Lambda n \) interaction is CSB (\( \Lambda p \) more attractive)**
- \( \Lambda \) in \( ^4_\Lambda \)He is more strongly bound than \( ^4_\Lambda \)H by \( 0.35 \pm 0.05 \text{ MeV} \) (~15%)
- Coulomb force correction makes the difference larger!
- After Coulomb force correction, this difference is \(~5 \text{ times larger}\) than in \(^3_\Lambda \)H -- \(^3 \)He case (i.e. for neutron energies)
- The reason is not yet fully understood, possibilities include
  - \( \Lambda / \Sigma^0 \) mixing in free space \( \rightarrow \pi^0 \) exchange force (tensor) ??
  - **\( \Lambda N-\Sigma N \) coupling** sensitive to mass difference of initial/final state
    \( \Delta m(\Lambda p \rightarrow \Sigma^+ n) \sim 75 \text{ MeV} < \Delta m(\Lambda n \rightarrow \Sigma^- n) \sim 80.5 \text{ MeV} \)
    \( \rightarrow \) **three-body force** as well as two body force.
  - \( K^0 \) and \( K^\pm \) mass difference (~1%), also in \( K^* \)
  - \( \rho/\omega \) mixing \( \rightarrow \) spin-orbit
- These are strongly spin dependent
- \( \rightarrow \) **spin/state dependence is important**
ΛΛ interaction

- Unique channel in SU(3) BB interaction classification
- Repulsive core may vanish in this channel
  → possibile existence of H-dibaryon (uuddss, J=I=0)
- Original prediction by Jaffe (PRL38 (1977) 195)
  - H is 80 MeV bound from ΛΛ
- No experimental evidence so far
  - at least, deeply bound H is rejected
- ΛΛ – ΞN (− ΣΣ) coupling important
- ΛΛ interaction study performed by
  - ΛΛ hypernuclei
  - ΛΛ final state interaction in (K−,K+) reaction
    (J. K. Ahn et al., PLB444 (1998) 267)
- Present data suggests ΛΛ interaction is weakly attractive
**ΣN interaction and Σ-hypernuclei**

- **Different** and more difficult to investigate than ΛN

- Σ has isospin 1 \((m_\Sigma \sim 1190\text{ MeV})\)
  - (long range) **OPE component** allowed
  - ΣN interaction both in \(T=3/2, 1/2\) (only \(1/2\) for Λ)

- Central part **weaker than ΛN** (strength of averaged potentials: NN/ΛN \(~3/2\) NN/ΣN \(~3\)) but still poorly known

- Strong **spin-isospin dependence** (due to exchange of isoscalar \((ω,η)\) and isovector \((π,ρ)\) mesons)
  - Potential form similar to Λ except \(V_i\) terms are **isospin dependent**
    - \((^1S_0, T=3/2)\), \((^3S_1, T=1/2)\): strong attraction,
    - \((^3S_1, T=3/2)\), \((^1S_0, T=1/2)\): weak repulsion

- **Spin-orbit** strength comparable to NN (0.5-1. MeV)

In Vacuum: \(Σ^\pm \rightarrow Nπ\)

In nuclei: \(ΣN \rightarrow ΛN\)
Sigma-Nucleon (ΣN) interaction and Σ-hypernuclei

- ΣN potential weaker than NN
  - Do Σ–Hypernuclei bind?
- The potential has a strong imaginary component due to the ΣN–ΛN Interaction (ImV~10-15MeV)
  - Large width (Γ~20-30MeV)

Do Σ–Hypernuclei have Narrow Structure?

Exp: 20 years ago narrow (<8MeV) peaks seen at CERN.
Theory: 20÷30 MeV expected in nuclear matter (ΣN→ΛN conversion creates a Λ with ~40MeV, which can escape the nucleus)

Exp. Situation very confusing; finally KEK exp.:

\[ ^4\text{He}(K^-, \pi^±) \] (PRL 80(1998)1605)

\[ ^4\Sigma\text{He} : 4.4 \text{ MeV Bound State; 7.0 MeV Width} \]
**ΣN interaction and Σ-hypernuclei**

Clear peak only in $^4\text{He}(K^-, \pi^-)$

No bound state in $^4\text{He}(K^-, \pi^+)$

$^4\text{He}(K^-, \pi^-)$: populates $T=1/2, 3/2$ states

$^4\text{He}(K^-, \pi^+)$: populates $T=3/2$ states

Since no bound state in $^4\text{He}(K^-, \pi^+)$

$\Sigma$ $^4\text{He}$ b.s. has $T=1/2$ and $T=1/2$ attractive, $T=3/2$ strongly repulsive

Possible width suppressing mechanisms

- $\Sigma \to \Lambda$ conversion less efficient (width decrease) because S-wave w.function considerably out of the nucleus due to shallow $\Sigma$-nucleus potential (especially in $T=3/2$ ch.)

- Pauli blocking effect on final nucleon in $\Sigma N \to \Lambda N$

- suppression of particular spin-isospin transitions

- medium polarization effects
The existence of $\Sigma$-hypernuclei heavier than $^4\text{He}$ is still an open question.

Data on medium-heavy $\Sigma$-hypernuclei useful to better understand $\Sigma$-nucleus potential, crucial for the study of $\Sigma^-$ hypernuclei in dense nuclear matter (neutron stars)
Impact on other fields:

**YN interaction and astrophysical objects**

Strange matter not in everyday life but most likely

**hyperons in neutron stars** (Neutron star =“giant hypernucleus” [SchaffnerBilichNPA804(‘08)])

hyperons populate deep lying states (no Pauli blocking)

→ **presence of hyperons energetically favoured**

- at large $n_B$ more general forms of matter, containing hadrons other than nucleons, may become energetically favored
- for example, $\Sigma^-$ can appear through the process

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

as soon as $\mu_n + \mu_e = M_{\Sigma^-}$.

- both NMBT and RMFT predict the appearance of $\Sigma^-$ at $n_B \sim 2 \ n_0$
- as the interactions between hyperons and nucleons are not as well known as those between nucleons, these calculations involve large uncertainties

1. **YN and YY interactions** determine **neutron stars E.o.S**
   (→ max N.S. mass)
2. **Non Mesonic Weak Decays** control **core viscosity**
   (macroscopic effects!)
Strongly interacting matter in neutron stars

“Strangeness” of dense matter?
In-medium properties of hadrons?
Nuclear matter equation of state?
Deconfinement at high baryon densities?
How to produce

Different production mechanisms can be used to form an hypernucleus:

**strangeness exchange reaction**

\[ K^- + n \rightarrow \Lambda + \pi^- \]  
(in flight, stopped) \( \sigma = 100 \text{ mb; } l_{\text{beam}} = 10^4 \text{ s}^{-1} \)

**associated production**

\[ \pi^+ + n \rightarrow \Lambda + K^+ \]  
\( \sigma = 1 \text{ mb; } l_{\text{beam}} = 10^7 \text{ s}^{-1} \)

\[ \gamma(e) + p \rightarrow \Lambda(\pi^0) + K^+ \]

**real and virtual photo- production**

\( \sigma = b; l_{\text{beam}} = 10^{10} \text{ s}^{-1} \)

In order to produce a hypernucleus, the hyperon emerging from the reaction has to remain inside the nuclear system. The formation probability of a hypernucleus depends on the energy transferred in the production.

When the momentum transferred to the hyperon is much larger than the nuclear Fermi momentum, the hyperon has a very small sticking probability and it leaves the nucleus. If it is smaller the hyperon is created, with a high probability, in a bound state.
Quark Flow Diagrams

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

\[ \pi^+ n \rightarrow \Lambda + K^+ \]

\[ \gamma + p \rightarrow \Lambda + K^+ \]

\[ K^- p \rightarrow \Lambda + \pi^0 \]
How to produce

• **Strangeness exchange** \((K^-,\pi^\pm)\) **reactions**
  - Transforms a nucleon in a \(\Lambda/\Sigma\) with emission of a \(\pi^\pm\) (hypn.
    levels from \(\pi\) spectrum)
  - reaction is esoenergetic \(\Rightarrow\) hyperon can be created at rest (if pion
    emitted at \(\theta=0^0\) and \(p_K\sim530\) MeV/c)
  - in general mom. transfer can be quite small

• at \(\theta=0^0\) hyperon produced predominantly with same quantum n.
  of nucleon (substitutional reaction,\(\Delta l=0\)). Increasing \(\theta\), the
  importance of \(\Delta l\ 1,2,…\) increases (access to hyp. with higher spin)

• \(K^-,\pi^\pm\) strongly absorbed by nucleus \(\Rightarrow\) preferentially populate
  less bound \(\Lambda\)-levels (used mostly for s,p-shell nuclei)
• **Strangeness exchange** \((\text{stopped}K^-,\pi^\pm)\) reaction

stopped \(K^-\) captured into atomic level \(\rightarrow\) cascades to inner levels \(\rightarrow\) absorbed at nuclear surface creating \(\Lambda\) (\(\Sigma\)). Momentum transferred \(\cong k_F (\Lambda:\sim 250\text{MeV/c})\)

- large production yield. High background
How to produce

- production of \(\bar{s}s\) pair
- large momentum transfer \((q > 350 \text{ MeV/c} \at \theta_{\text{scatt}})\) → hyperon can be produced above emission threshold. Some hypn. state in continuum may be quasi-bound states (they emit [clusters of] nucleons)
- well suited for studying deeply bound states in medium-heavy hypernuclei (populates states with high \((n^{-1},\Lambda)\) spin configurations)
- small cross section, but intense \(\pi\) beam available
Weak decay of hypernuclei.

[In general decays with $\gamma$,N,clusters... possible if highly excited hypn.]

**Mesonic decay**

Once a $\Lambda$ is formed, regardless the capture shell level, it quickly cascades to $(1S_{1/2})$ state (emitting $\gamma$’s).

- In free space $n$, $\Lambda$ unstable (**weak decay**):
  
  $n \rightarrow p + e + \bar{\nu}$ \hspace{1cm} ($\tau_n \sim 10^3 s$)

  $\Lambda \rightarrow N + \pi$ (101MeV/c) \hspace{1cm} ($\tau_\Lambda = 2.63 \times 10^{-10} s$) **mesonic decay**

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  $\rightarrow$ while neutron is stable inside nuclei, $\Lambda$ eventually decays.

The **decay nucleon momentum** (energy) in free space is

$\sim 100 \text{MeV/c}$ ($\sim 5 \text{MeV}$) which is below the Fermi momentum

$\rightarrow$ $\Lambda$ decay is Pauli blocked (strictly forbidden in infinite N.M. ($k_F \sim 270 \text{MeV/c}$))
Mesonic decay

Still, in finite nuclei can occur because (medium effects)

- Hyperon has momentum distribution (confined) → larger final nucleon momenta
- Binding of final pions → given momentum means less energy

\[ \omega(q) < \sqrt{q^2 + m_\pi^2} \] → more energy to the nucleon

→ **mesonic width increased** (factor 2 @ A=16, 2 o.of m. @ A=200 )

Mesonic decay → info on **pion-nucleus optical potential** (\(\Gamma_M\) very sensitive to \(\pi\) self-energy)

- **MD dominant only in very light hypernuclei** (\(A<6\))
- Well described by (phase space)*(Pauli effect)*\((\pi\) distortion)

\[ \pi^- \text{ decay partial width} \]

- Exp. data from
  - H. Outa et al., NPA639 (1998) 251c
  - V. J. Zeps et al., NPA639 (1998) 261c
Mesonic decay

- In free space... ($\Delta s=1$)
  \[ \Lambda \rightarrow p^- \quad (63.9\%, \; Q = 38 \text{ MeV}) = \frac{\Gamma_{\pi^-}}{\Gamma_{\Lambda}} \]
  \[ n^0 \quad (35.8\%, \; Q = 41 \text{ MeV}) = \frac{\Gamma_{\pi^0}}{\Gamma_{\Lambda}} \]

- $\Gamma_{\Lambda} = \Gamma_{\pi^-} + \Gamma_{\pi^0}$
  \[ \frac{\Gamma_{\pi^-}}{\Gamma_{\pi^0}} \sim 2 \]

- Initial state: $I=0$, final state: $I=1/2$ or $3/2$
  $\Delta I=1/2$ or $3/2$ theoretical equivalent (weak hamiltonian)
    - if $I_f = 1/2$, \[ \frac{\Gamma_{\pi^-}}{\Gamma_{\pi^0}} = 2:1 \]
    - $3/2$, \[ \frac{\Gamma_{\pi^-}}{\Gamma_{\pi^0}} = 1:2 \]

  Experimentally \[ \frac{\Gamma_{\pi^-}}{\Gamma_{\pi^0}} \sim 2 \] which is consistent with pure $I=1/2$ (I=1/2 amplitude enhanced by ~20)

  $I=1/2$ rule holds

is general rule in strangeness decay, but not clearly understood

- Inside nuclei the $I=1/2$ (for closed shell, symmetric n.) holds, but strongly dependent on hypernuclear structure.

**Note: $\Delta I=1/2$ rule holds for all strangeness-changing non-leptonic processes**
Weak decay of hypernuclei

Non-mesonic decay

- Mesonic decay is suppressed in hypernuclei due to Pauli blocking for the final state nucleon.
- Therefore, non-mesonic (NM) decay dominates in hypernuclei

\[
\begin{align*}
\Lambda p & \rightarrow n p, \quad (\Gamma_p) \\
\Lambda n & \rightarrow n n, \quad (\Gamma_n) \\
\Lambda NN & \rightarrow nNN \quad (\Gamma_2)
\end{align*}
\]

Total weak decay rate is \( \Gamma_T = \Gamma_M + \Gamma_{NM} \) \( \tau = \frac{1}{\Gamma} \)

NM decay can be interpreted as a M decay where the virtual pion is absorbed by one (a pair of) nucleon(s).

\[ Q \sim m_\Lambda - M_n \sim 176 \text{ MeV} \text{, i.e. } p_N \sim 420 \text{ MeV/c} \]  
\[ (340 \text{ MeV/c for 2-nucleon induced}) \]

Pauli-blocked \hspace{1cm} Not Pauli-blocked

High mom. Transf. \( \rightarrow \) short distances probe (quark-gluon d.of f.)
Non-mesonic decay

NM mechanism dominates over M for all but s-shell hyp.

NM decay is only possible in nuclei and can be mediated by the exchange of more massive mesons.

Study of weak interaction between nucleons difficult (PC part masked by strong int.).

NMWD only practical way to study weak interaction between barions.
Non-mesonic decay

NM channel $\rightarrow$ large momentum transfer
$\rightarrow$ details of hypn. structure negligible (except very light hypn.)
$\rightarrow$ $\Lambda N$, NN short range correlation very important

Anticorrelation between M and NM decay modes $\rightarrow \tau_\Lambda (\Gamma_{tot})$
quite stable from light to heavy hypn. (except few cases).
This is because NM rate rather constant in heavy hypn.
(in a zero-range approx. $\Gamma_n + \Gamma_p$ proportional to overlap of $\Lambda$ and nuclear densities, which saturates for $A>65$)
Weak decay

• Almost constant for $A > 10$
• non-mesonic decay dominant (short range nature of nonmesonic decay)

Lifetime measurements

• exp. data from
  H. Park et al., PRC61 (2000) 054004
  H. Outa et al., NPA639 (1998) 251c
  V. J. Zeps et al., NPA639 (1998) 261c
  J. J. Szymanski et al., PRC43 (1991) 849
  R. Grace et al., PRL55 (1985) 1055
Non-mesonic decay: $\Gamma_n/\Gamma_p$ puzzle

- Simplest diagram for non-mesonic weak decay
  -- one pion exchange

- Virtual mesonic decay +absorption
  - $(\Lambda N)^3S_1 \to (NN)^3D_1$ tensor
    coupling $\Delta L=2, \Delta S=2$ has the largest amplitude, but this is forbidden for $(nn)$ final state.

- This model predicts
  $$\Gamma_n (n\Lambda \to nn) << \Gamma_p (p\Lambda \to pn)$$

- However, experimental data (before ~2003) indicate
  $$\Gamma_n/\Gamma_p \sim 1$$
  (e.g., H. Hashimoto et al., PRL88 (2002) 042503)

<table>
<thead>
<tr>
<th>OPE</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_n/\Gamma_p$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

with large error

This was the situation till ~2003.....
Non-mesonic decay: $\Gamma_n/\Gamma_p$ puzzle

Experimentally very challenging
Huge (60% for $^5\Lambda$He) data error on $n/p$

Experimental problems:

• high proton threshold (usually~30MeV)
• Low neutron efficiencies
• Large error bars

Problems in determination method of $\Gamma_n/\Gamma_p$ ratio from data

1) model dependent

2) Effects of FSI (low en. protons from FSI) and 2N process
(if $\Lambda NN \rightarrow NNN$ large, then $\Gamma_n$ overestimated if thresh. on low energy protons present)
Non-mesonic decay: $\Gamma_n/\Gamma_p$ puzzle.

**Theory**

Several attempts made to solve the puzzle:

- **Additional meson exchange?**
  $\rightarrow K (\eta, \rho, \omega, K^*, \ldots)$ meson

- **Improve the situation, but still below exp. data.**
  (e.g., E. Oset et al., NPA691 (2001) 146c)

- **Some models also incorporate $2\pi$ exchange processes**
  (e.g., K. Itonaga et al., NPA639 (1998) 329c)

- **Direct quark mechanism?**
  - s-quark decays directly without meson propagation
    (e.g., M. Oka, NPA691 (2001) 364c)

- **Two nucleon induced processes?** (\(\Lambda NN \rightarrow NNN\))
\[ \frac{\Gamma_n}{\Gamma_p} \text{ puzzle: towards a solution?} \]

**Recent Development of OME, DQ model**

**Recent Exp. Development:**
- \( e \sim 0.5 \)
- \( e \sim 0.3 \sim 0.7 \)

**Exp.**

**Singles**
- \(^5\He : 0.61 \pm 0.081 \pm 0.082 \) (E462)
- \(^{12}\He : 0.58 \pm 0.06 \pm 0.08 \) (E508)
- \( \pm 0.15 \) (E307/E369)

**Coincidence**
- \(^5\He : 0.43 \pm 0.12 \pm 0.044 \) (E462)
- \(^{12}\He : 0.34 \pm 0.13 \pm 0.05 \) (E508)
NM Weak decay of Λ hypernuclei

NMWD: study of baryon-baryon weak interaction (and 3-baryons ΛNN int.)
Slightly affected by nuclear structure (mom. Tranfer ~400MeV/c), test of
short range correlations, Δl=1/2 rule, quark d.o.f., rare decays…

Strong disagreement between exp. and theory until recently
\[ \Gamma_n/\Gamma_p \text{ puzzle: OPE: } \Gamma_n/\Gamma_p \sim 0.1; \text{ EXP : } \Gamma_n/\Gamma_p \sim 1 \]

- Experimentally difficult
  - Hyp.nucleus identification (π)+ p/n detection necessary.
  - High proton thresholds: low energy region missing (FSI and 2-N induced
decays), model dependent data analysis → \( \Gamma_n/\Gamma_p \) puzzle unresolved for several years
- Theory: OPE + kaons + heavier mesons exch.+ direct quark mechanisms

\( \Gamma_n/\Gamma_p \text{ puzzle solved in correlated } p/n \text{ back-to-back kinematics +non-trivial data interpretation} \)
(no FSI, no 2N abs)

\[ ^{12}_Λ \text{C: OME } \Gamma_n/\Gamma_p \sim 0.4 \ [\text{Garbarino,PRC69(04)}]; \text{ EXP(KEK) : } \Gamma_n/\Gamma_p \sim 0.4 \ [\text{Kang,PRL96('06)}] \]

Single proton spectra still incompatible with theor. predictions (Bauer et al,nucl-th/0602066)

More in the next lessons…