Updated results on ${}_{\Lambda}^{11}B$ and ${}_{\Lambda}^{12}C$ γ-ray spectroscopy study

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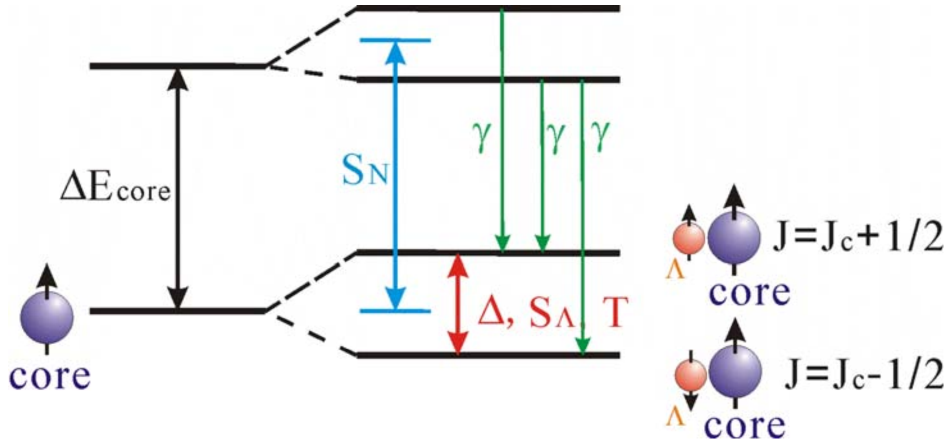
Outline of the presentation

- Introduction:
  - spin-dependent ΛN interaction
  - motivation of the KEK-E566 experiment
- Experiment:
  - detectors & experimental setup
- Analysis:
  - hypernuclear γ-ray spectrum analysis
  - hypernuclear level schemes
- Result & Discussion
  - spin-dependent ΛN interactions: S_N , Δ
  - ΛΣ coupling effects for p-shell hypernuclei
- Summary

Hypernuclear fine structure: theoretical approach

Keyword: shell model, weak coupling



$$V = \overline{V_0} + \Delta \cdot \sum_{i=1}^{A-5} s_{Ni} \cdot s_\Lambda + S_\Lambda \cdot \sum_{i=1}^{A-5} l_{N\Lambda i} \cdot s_\Lambda + S_N \cdot \sum_{i=1}^{A-5} l_{N\Lambda i} \cdot s_N + T \cdot \sum_{i=1}^{A-5} \left\{ \frac{3(s_\Lambda \cdot r)(s_{Ni} \cdot r)}{r^2} - s_\Lambda \cdot s_{Ni} \right\}$$

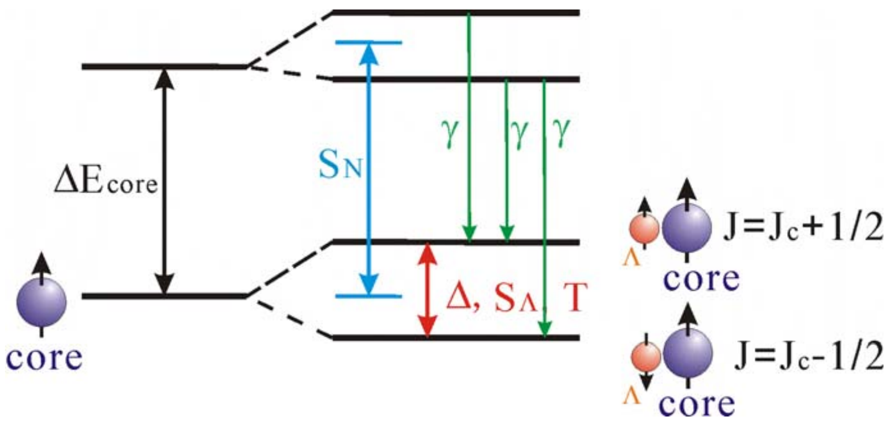
$$\Delta = \int \Psi_{N\Lambda}{}^* V_\sigma \Psi_{N\Lambda} dr, \quad S_\Lambda = \int \Psi_{N\Lambda}{}^* V_\Lambda \Psi_{N\Lambda} dr,$$

$$S_N = \int \Psi_{N\Lambda}{}^* V_N \Psi_{N\Lambda} dr, \quad T = \int \Psi_{N\Lambda}{}^* V_T \Psi_{N\Lambda} dr,$$

where $\Psi_{N\Lambda} = p_N \cdot s_\Lambda$ and V_i is calculated from free space ΛN interaction (NCS97e, f) via G - matrix.

Hypernuclear fine structure: experimental approach

Keyword: high resolution, high counting rate



- High resolution: Ge detector is necessary (Hyperball)
- High counting rate: reset-type preamplifier
- High background level: BGO counter

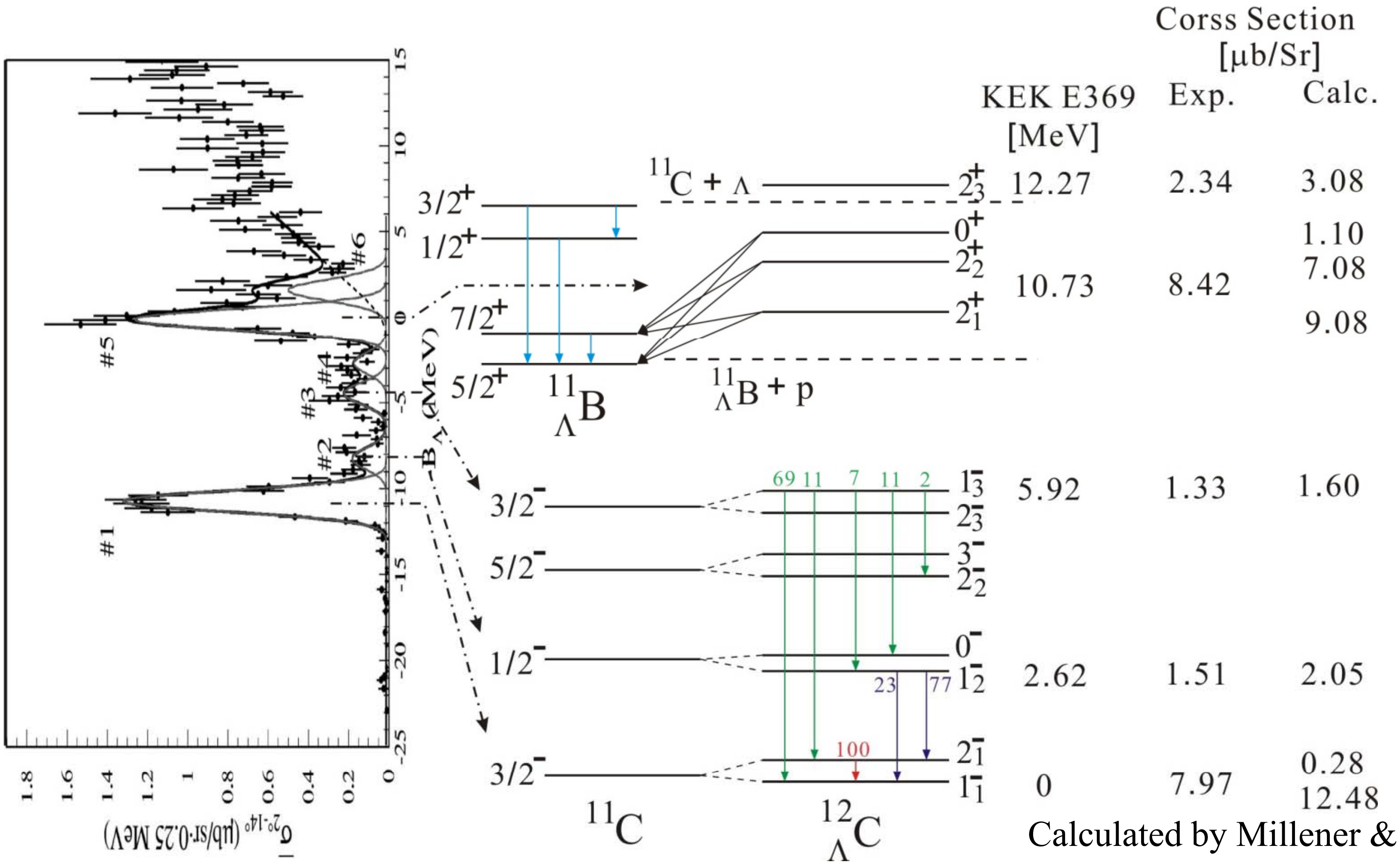
Δ = 0.43 [MeV]; S_N = -0.4 [MeV];
S_Λ = -0.015 [MeV]; T = 0.03 [MeV];

Can not reproduce ground state doublet spacing of ${}_{\Lambda}^{10}B$.

Motivation of KEK-E566: $^{12}C(\pi^+, K^+)_{\Lambda}{}^{12}C/_{\Lambda}{}^{11}B+p$

- Interaction parameters consistency check
- ΛNN interaction (ΛΣ coupling): $_{\Lambda}{}^{10}B$ puzzle

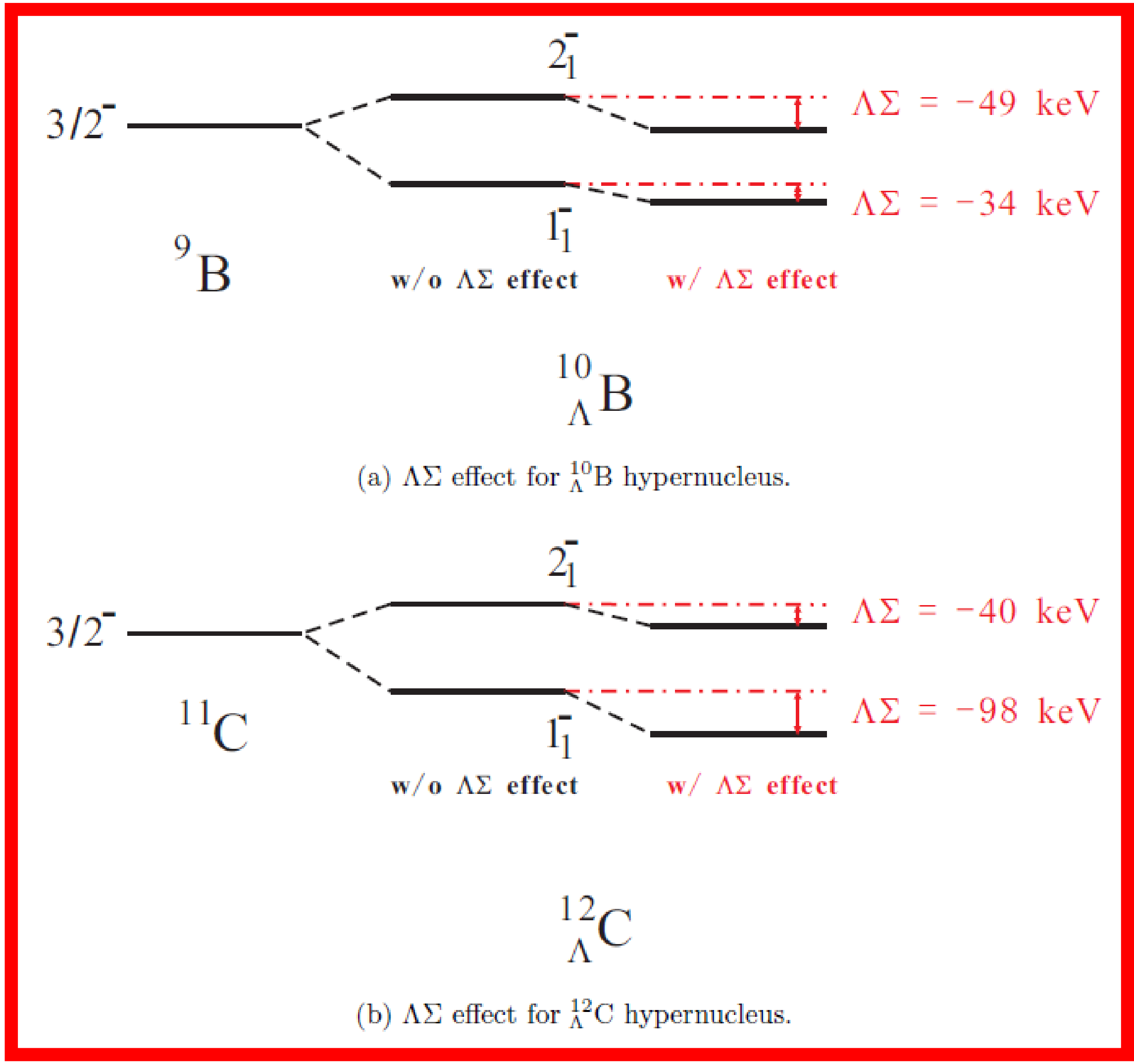
Reaction spectroscopy (KEK-E369)

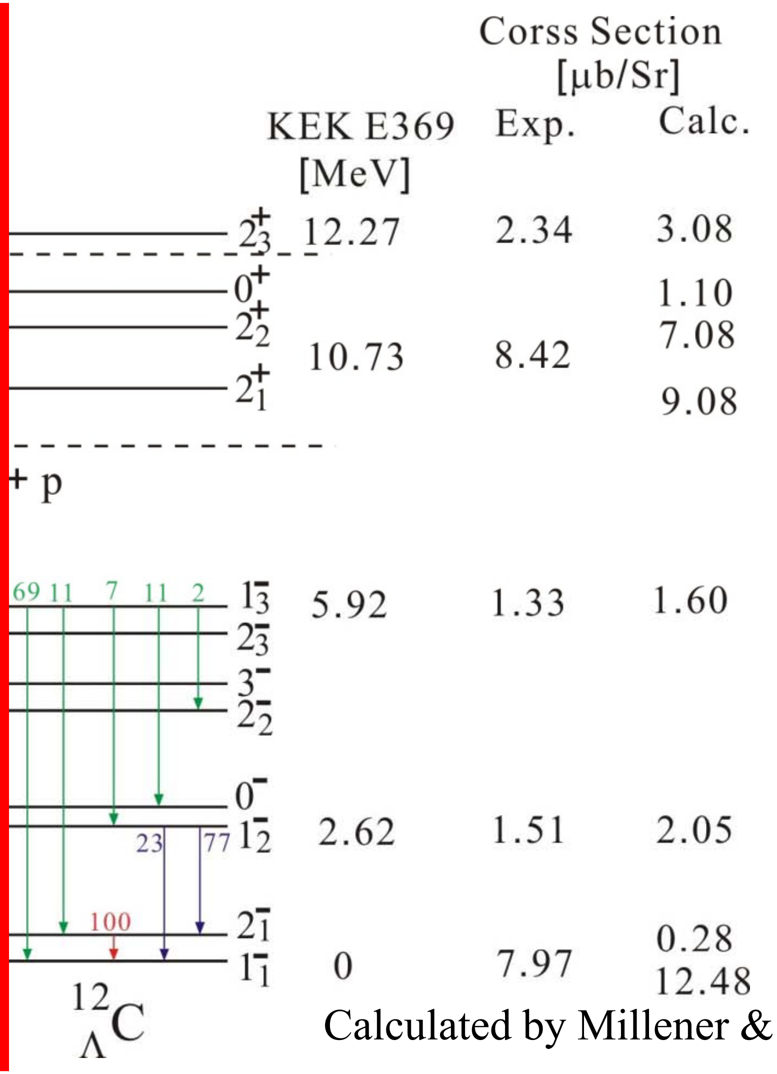


Calculated by Millener & Itonaga

Motivation of KEK-E566: $^{12}C(\pi^+, K^+)_\Lambda{}^{12}C/{}_\Lambda{}^{11}B+p$

- ➢Interaction parameters consistency check
- ➢ΛNN interaction (ΛΣ coupling): $_\Lambda{}^{10}B$ puzzle



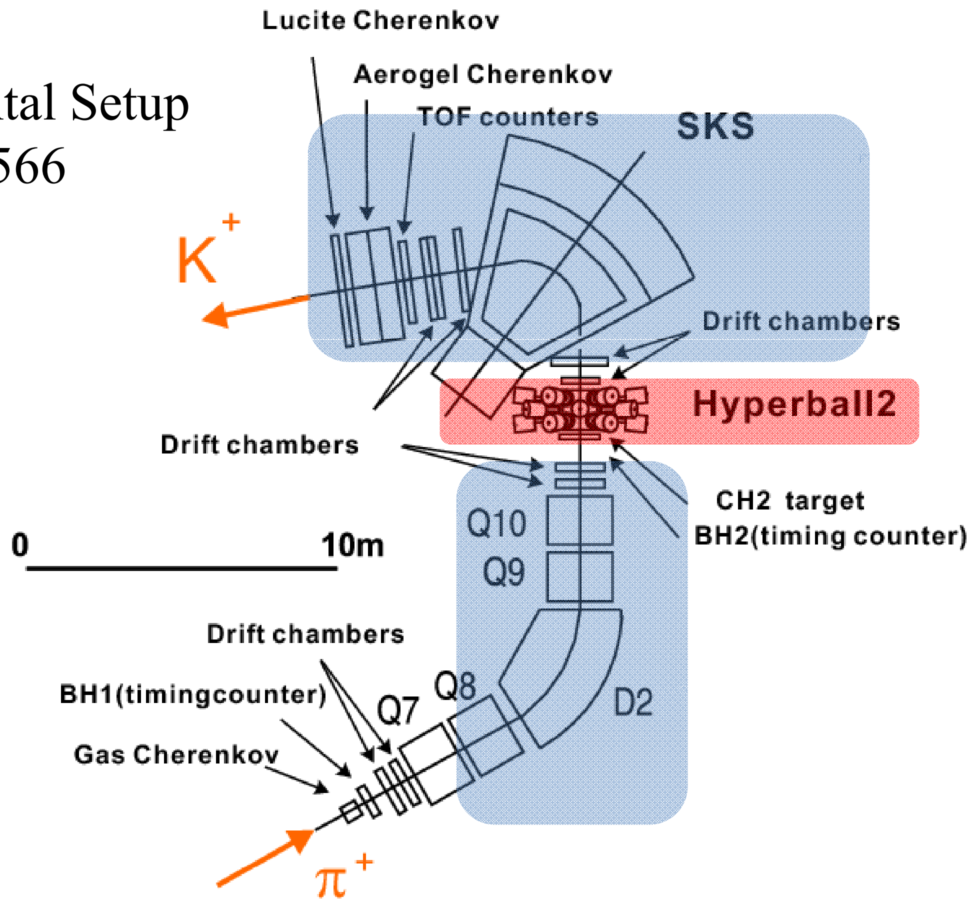


Calculated by Millener & Itonaga

$^{12}C(\pi^+, K^+)_\Lambda{}^{12}C/_\Lambda{}^{11}B+p$

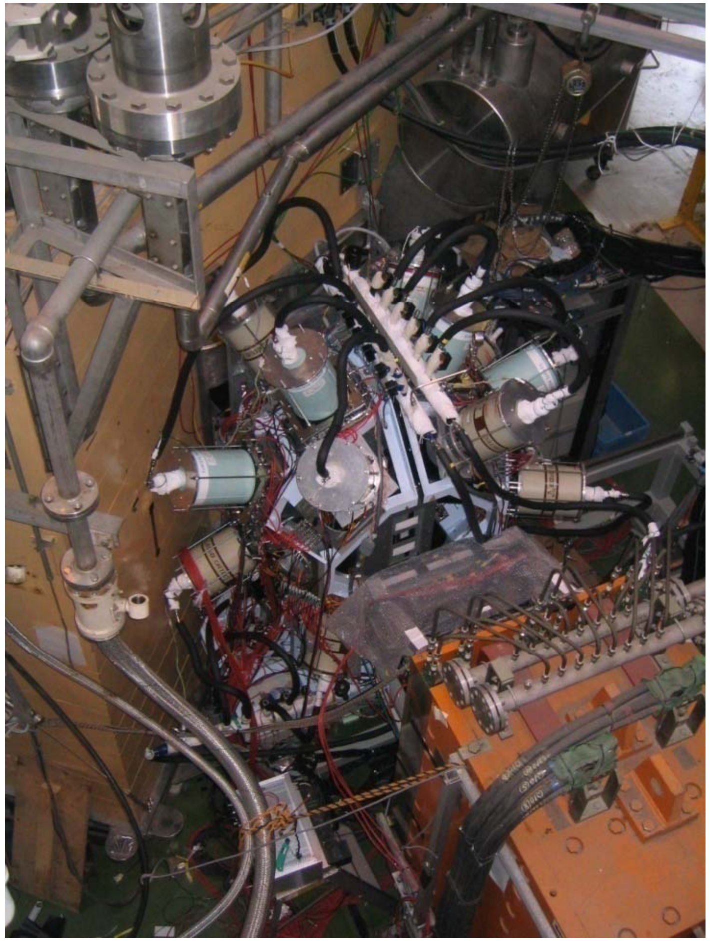
The last hypernuclear experiment @ KEK-PS

Experimental Setup of KEK-E566

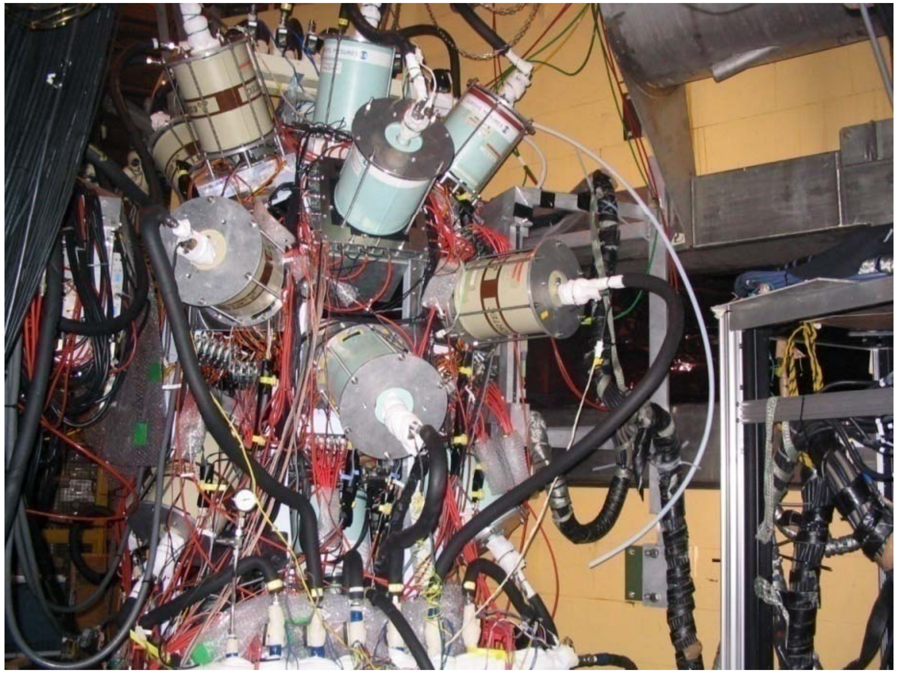


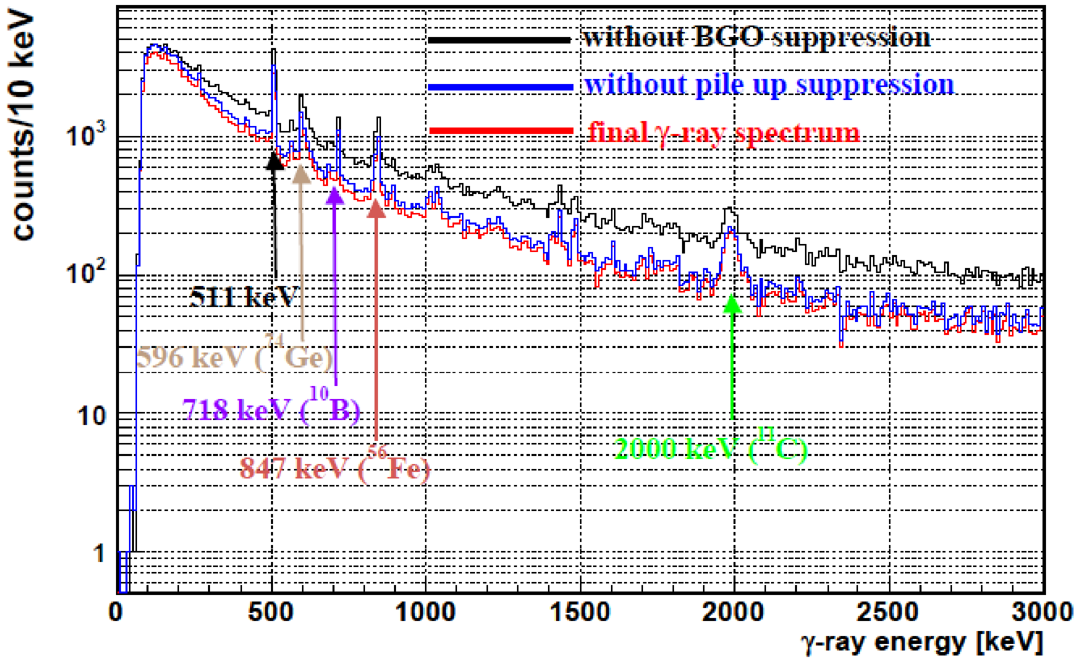
1.05 GeV/c
3×10^6/spill

Totally $2\times10^{12}\pi^+$



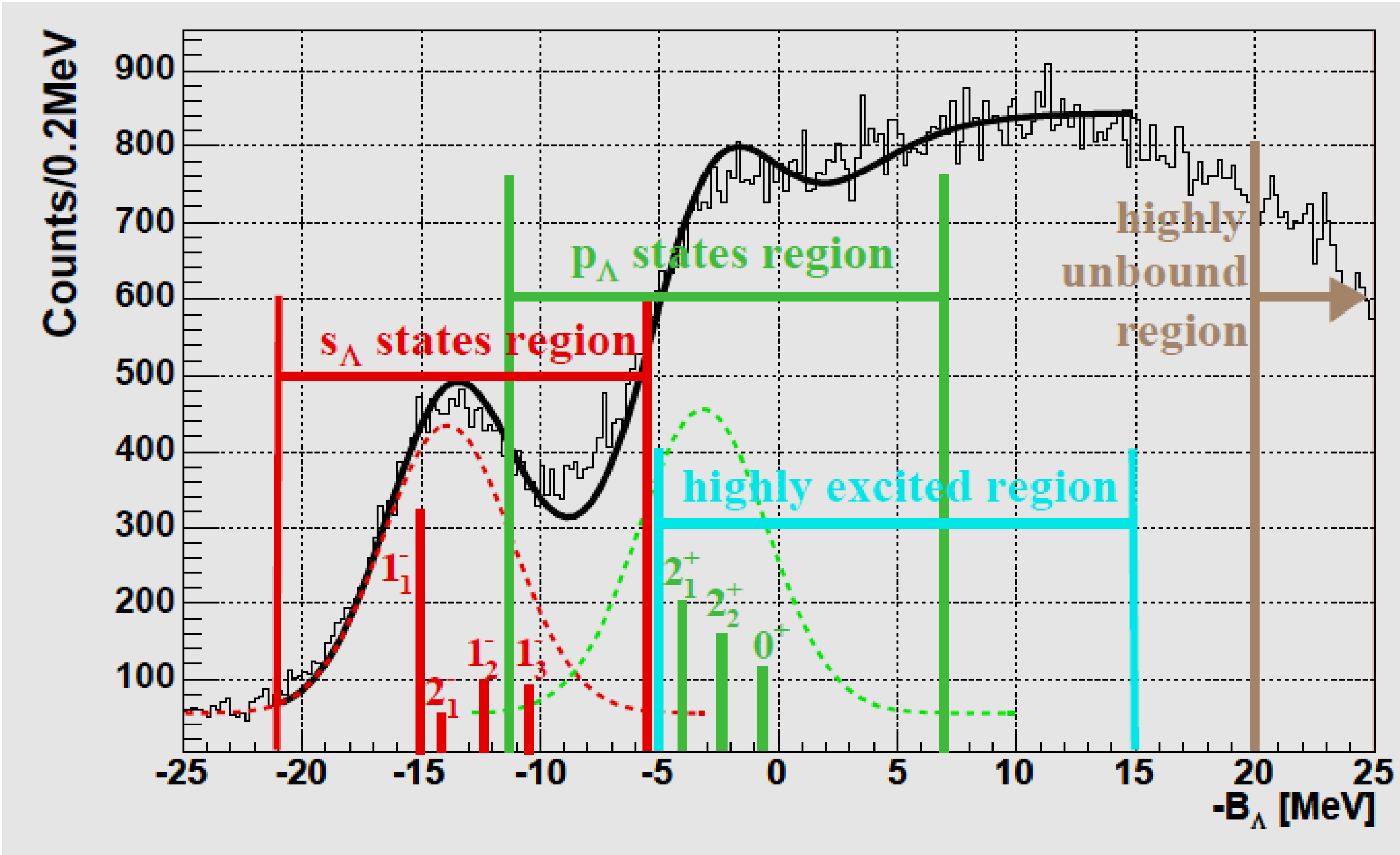
Hyperball2: Ge detector array with BGO counter





- Photo-peak efficiency: 3.9% @ 1.33 MeV when beam off;
- Photo-peak efficiency: 2.0% @ 1.33 MeV when beam on;
- Energy resolution: 5.3 keV (FWHM) @ 1.33 MeV when beam on.

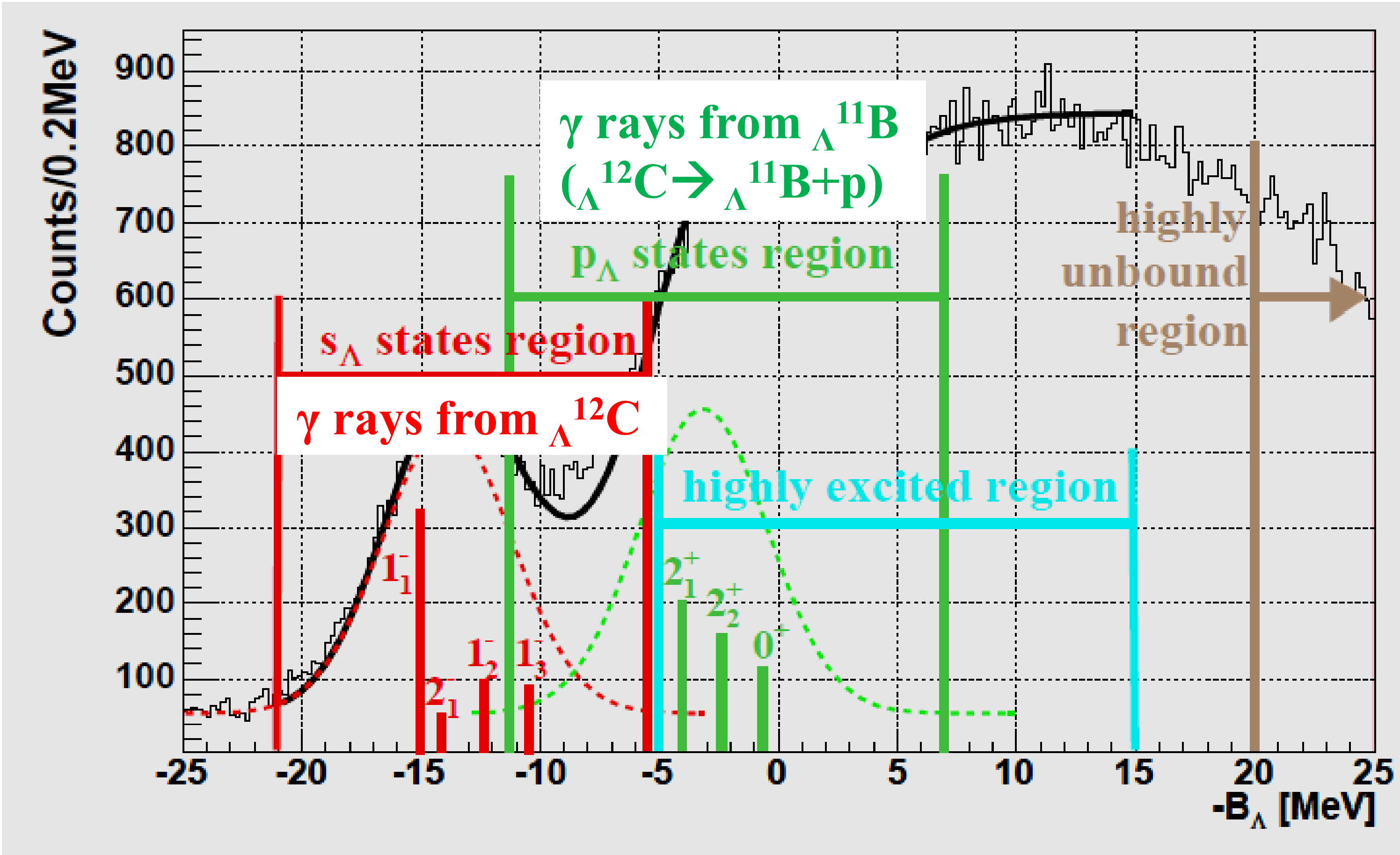
Hypernuclear states selection



Λ hyperon binding energy of ${}_{\Lambda}^{12}C$

Energy resolution: ~7 MeV (FWHM)

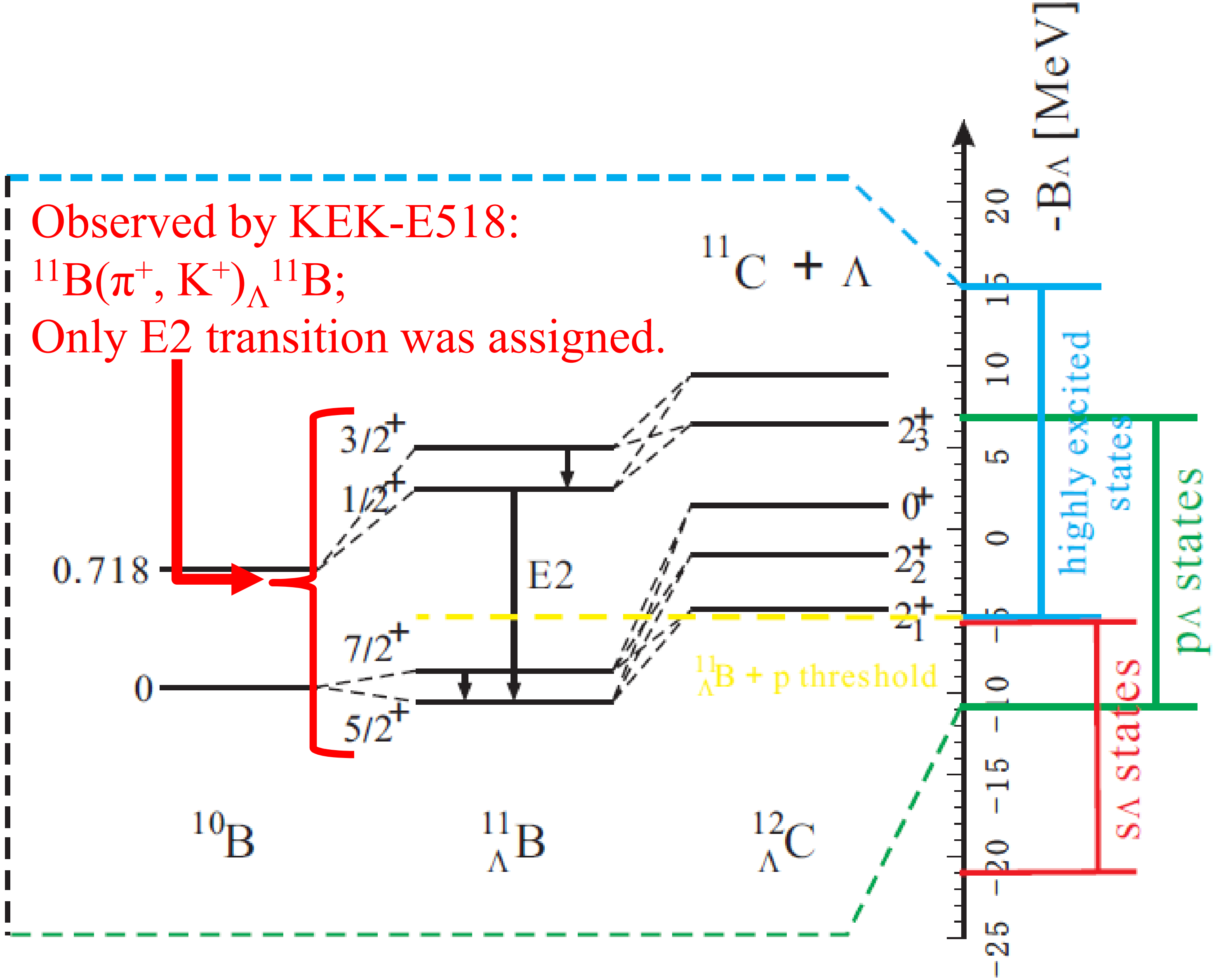
Hypernuclear states selection



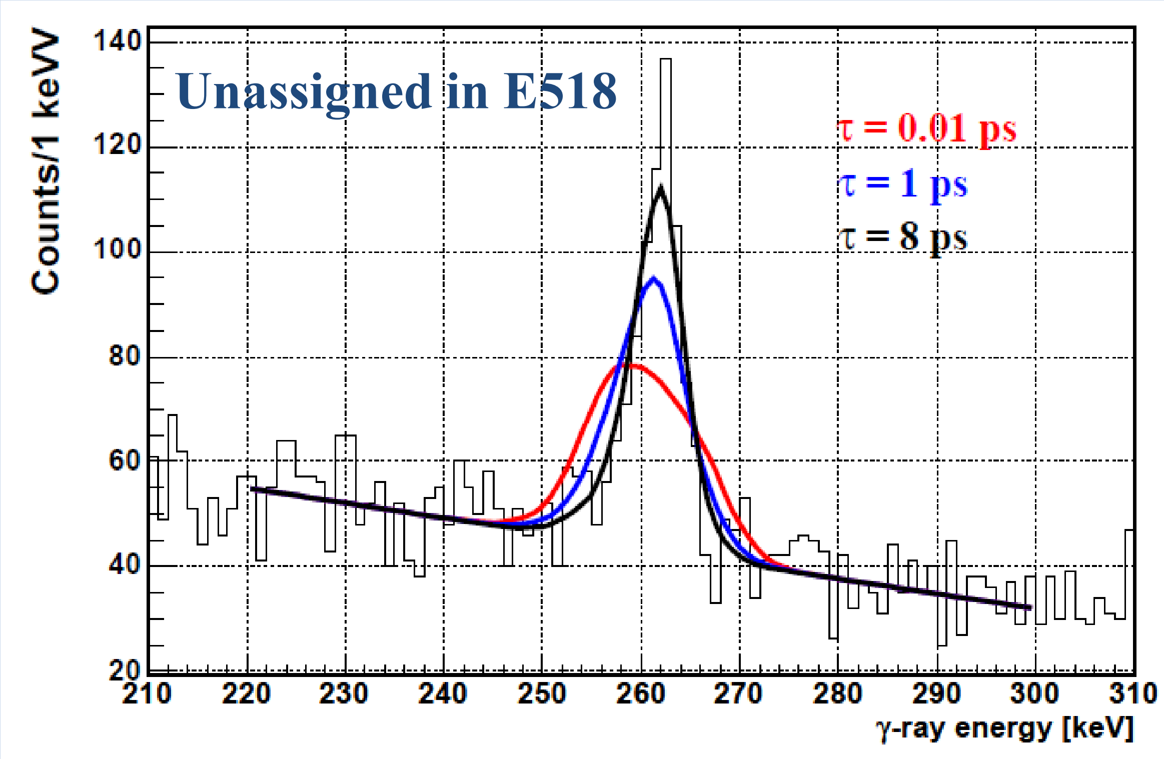
Λ hyperon binding energy of $_\Lambda{}^{12}$C

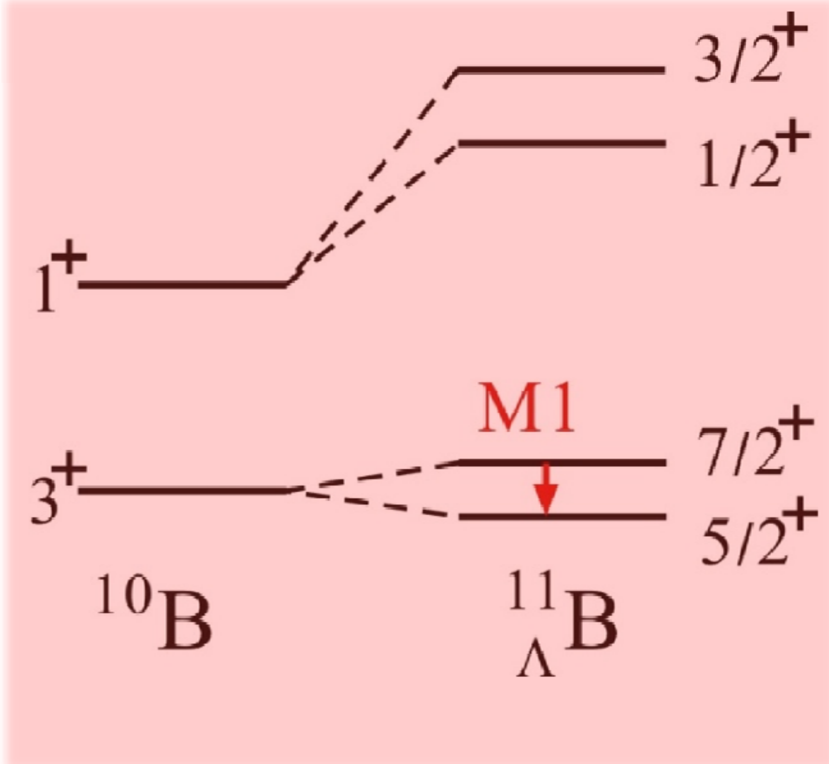
Energy resolution: ~7 MeV (FWHM)

γ-ray spectrum from $_{\Lambda}{}^{11}B$ hypernucleus



γ-ray spectrum from $_{\Lambda}{}^{11}$B hypernucleus: spin assignment I

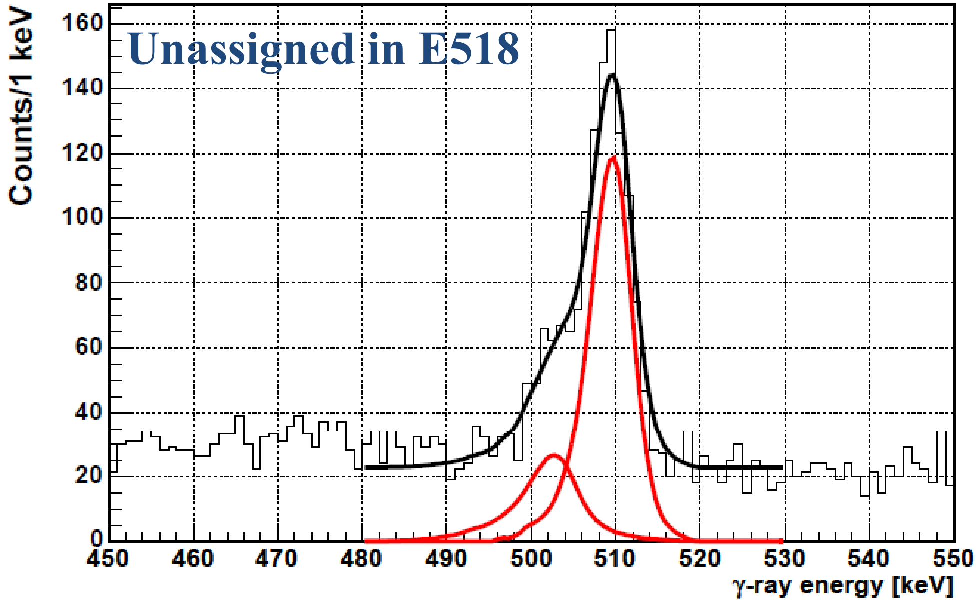


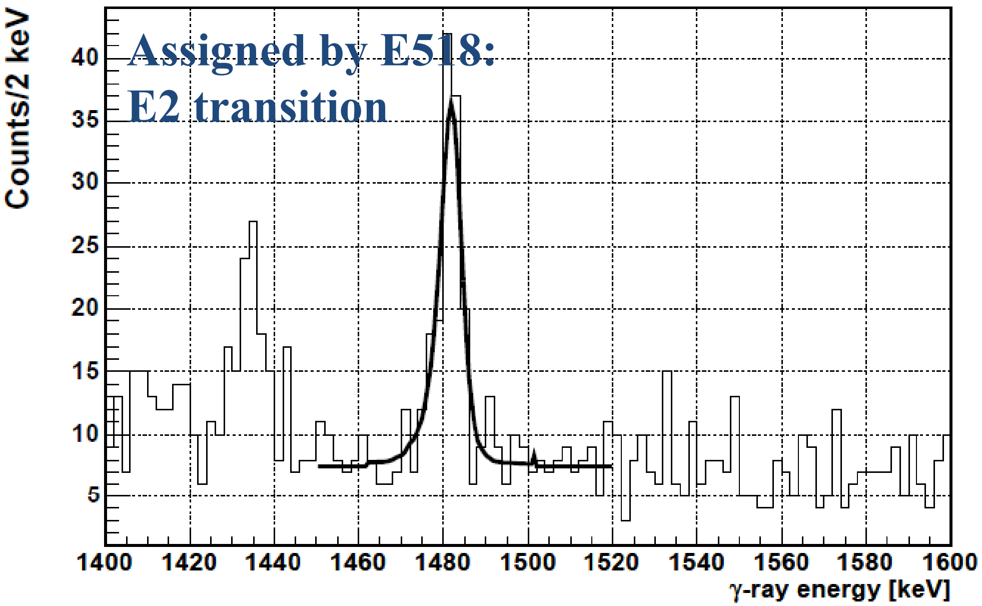


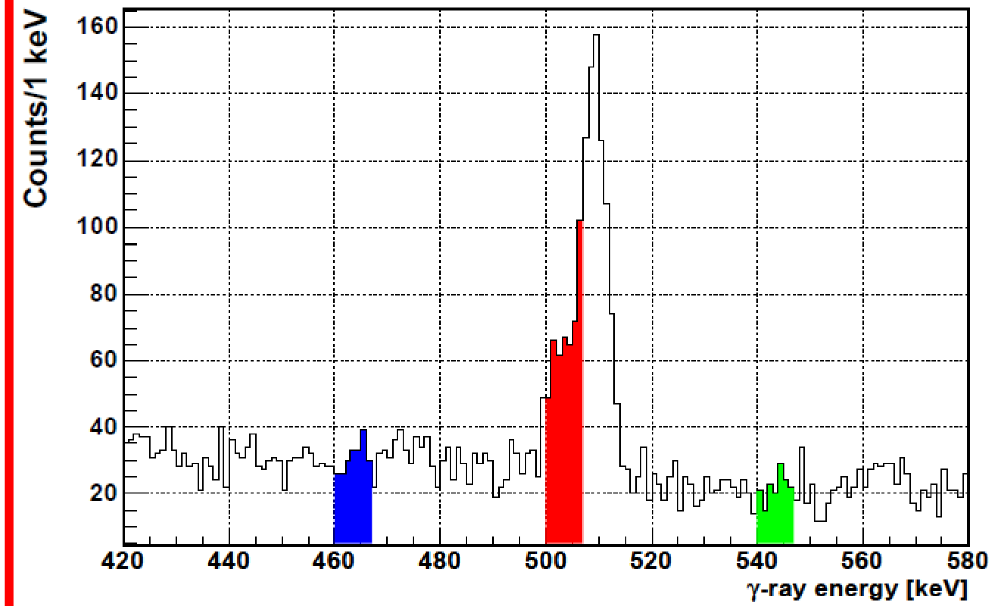
263 keV gamma ray was observed most prominently in the p_{Λ} states region. Other $_{\Lambda}{}^{11}$B excited states are too high to be populated from p_{Λ} states region.

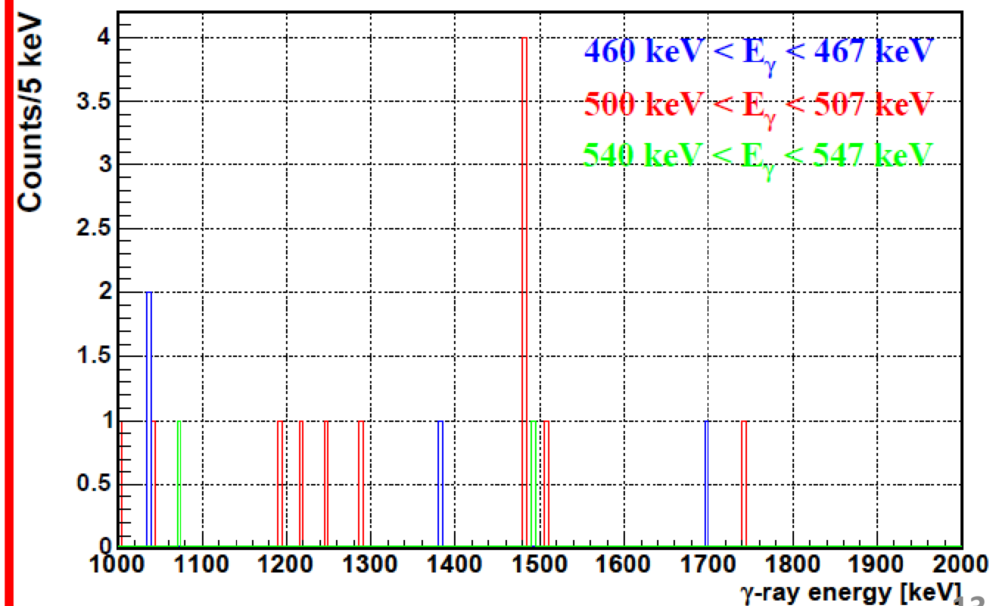
→ $_{\Lambda}{}^{11}\mathrm{B}(7/2^{+} \rightarrow 5/2^{+})$

γ-ray spectrum from $_{\Lambda}^{11}$B hypernucleus: spin assignment II





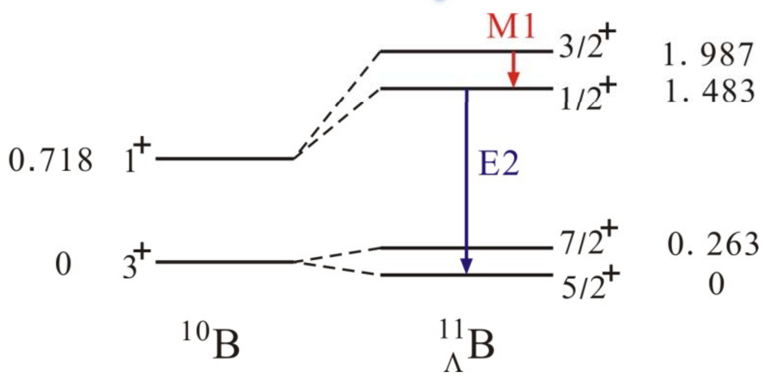


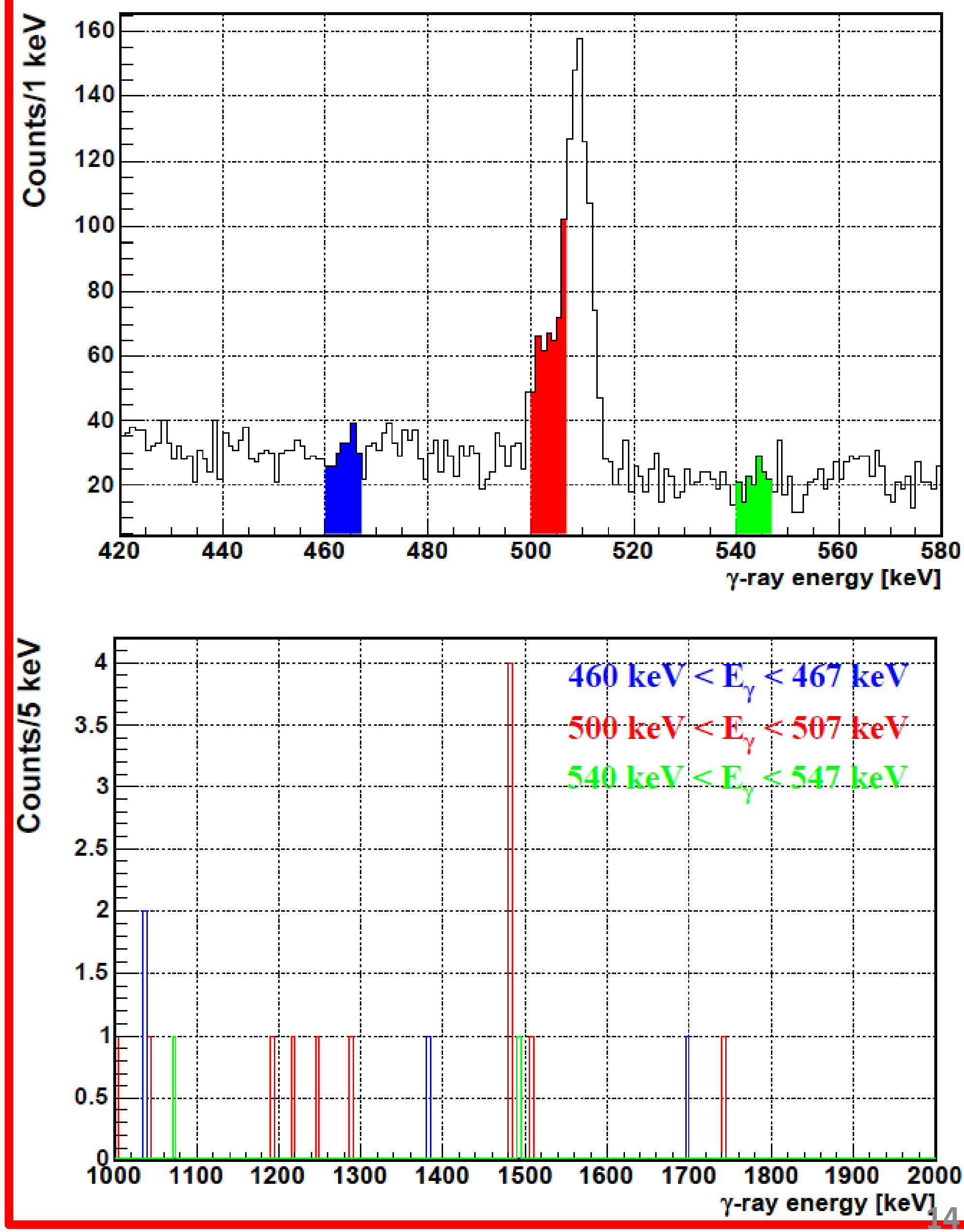


γ-ray spectrum from $_{\Lambda}^{11}$B hypernucleus: spin assignment II

$$P(\geq 4) = 1 - \sum_{i=0}^{3} p(i) = 1 - \sum_{i=0}^{3} \frac{0.05^i \cdot e^{-0.05}}{i!} = 6.1 \times 10^{-4}.$$

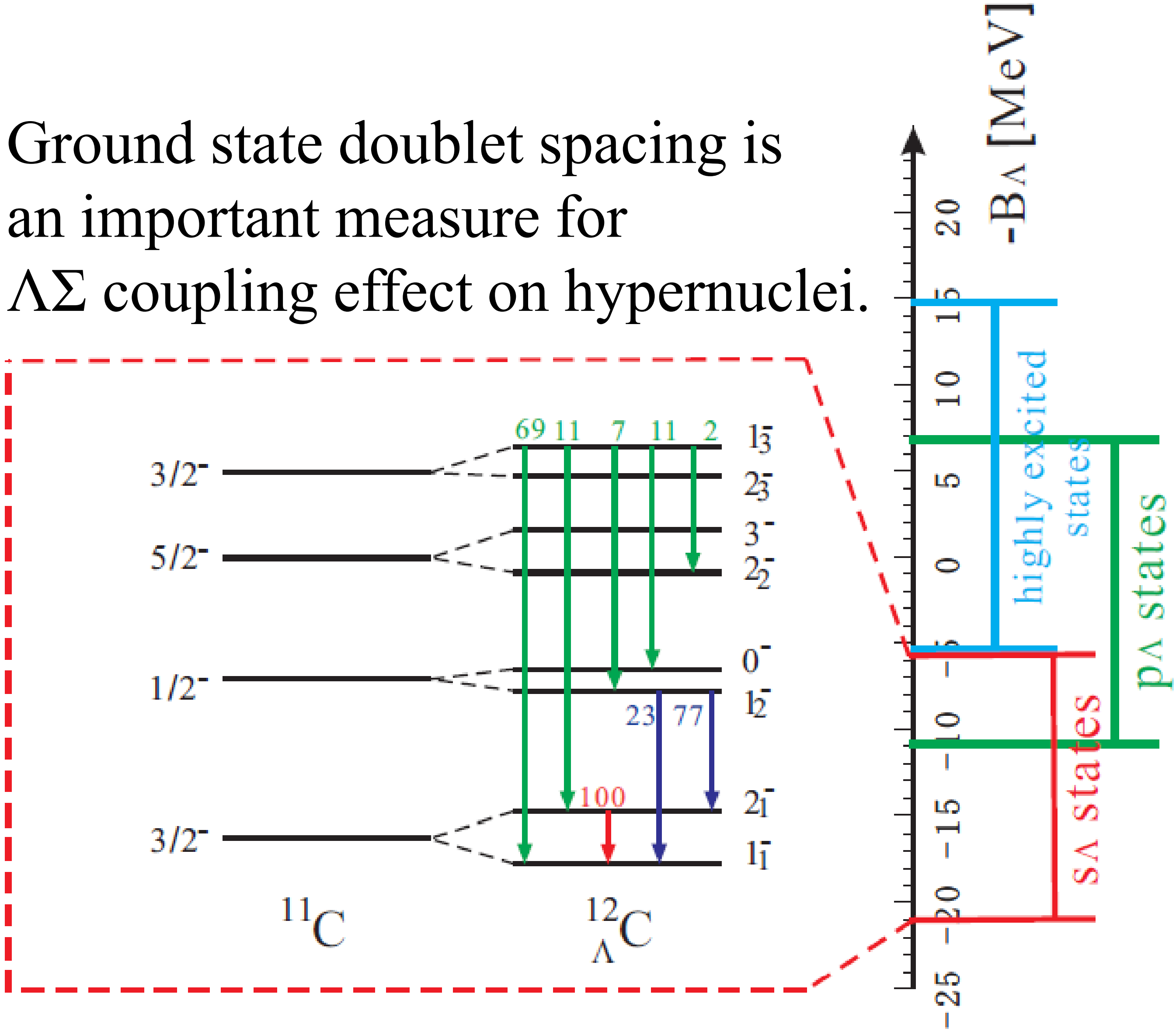
$_{\Lambda}^{11}$B($3/2^+ \rightarrow 1/2^+ \rightarrow 5/2^+$) transition



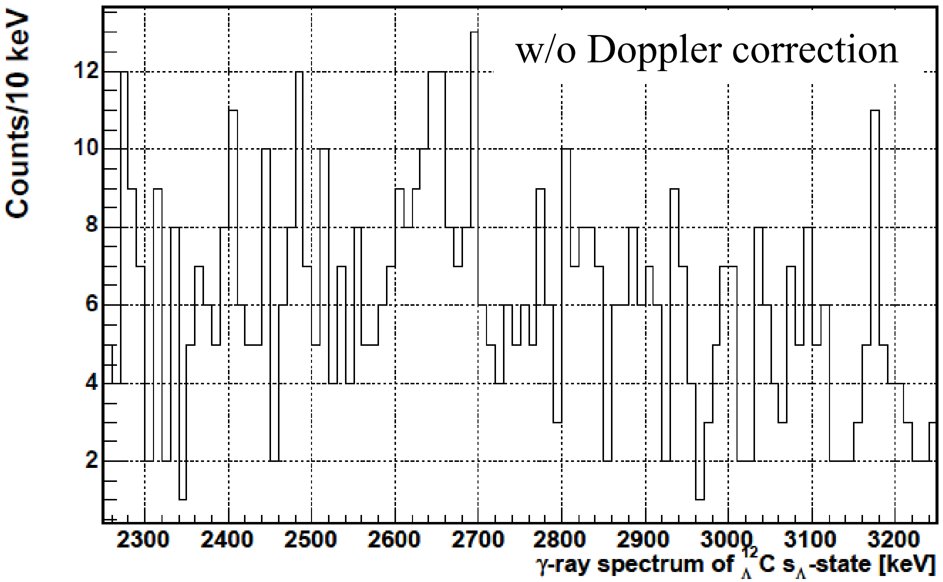


γ-ray spectrum from ${}_{\Lambda}^{12}C$ hypernucleus

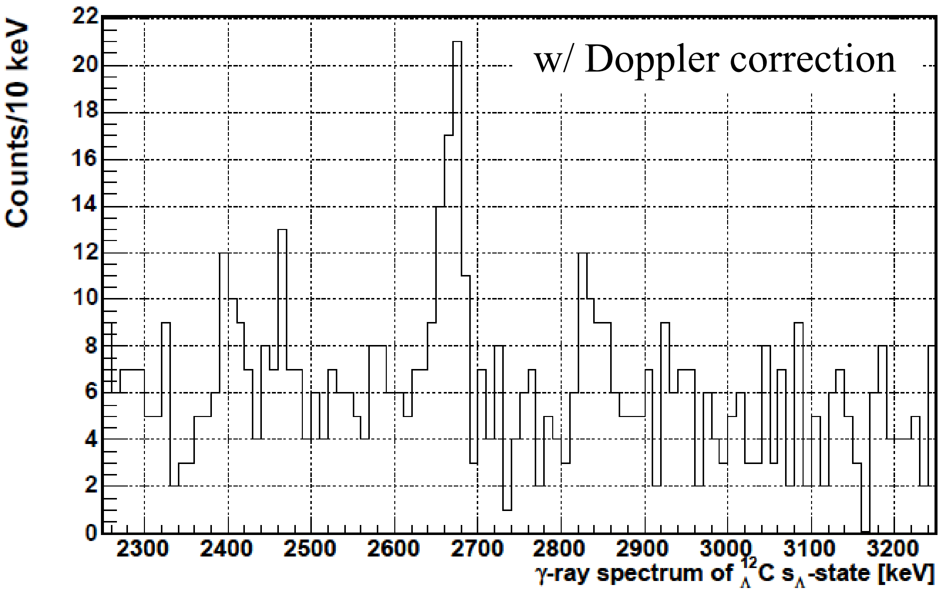
Ground state doublet spacing is
an important measure for
ΛΣ coupling effect on hypernuclei.

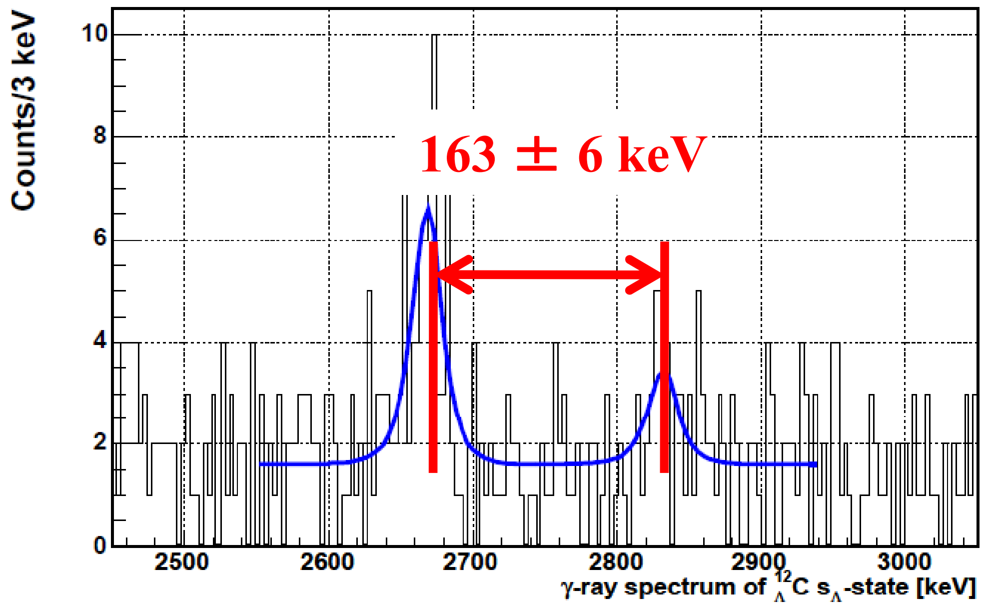


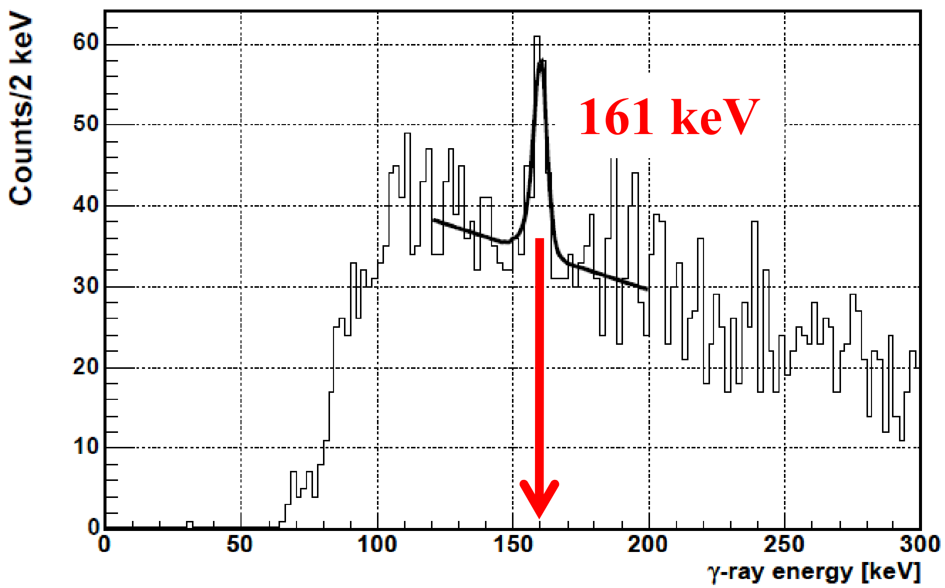
γ-ray spectrum from $_{\Lambda}{}^{12}C$ hypernucleus: spin assignment

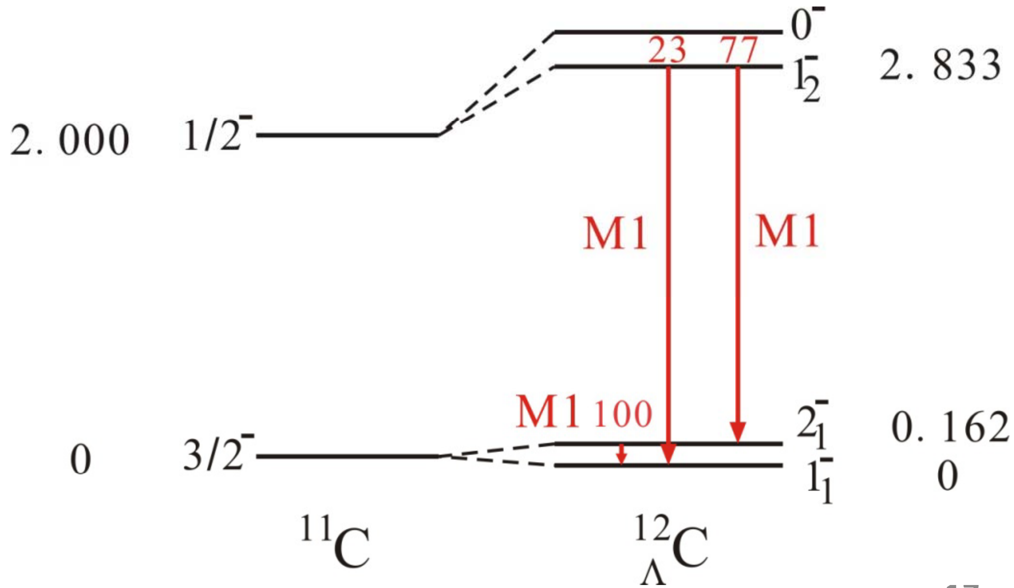


γ-ray spectrum from $_{\Lambda}^{12}C$ hypernucleus: spin assignment



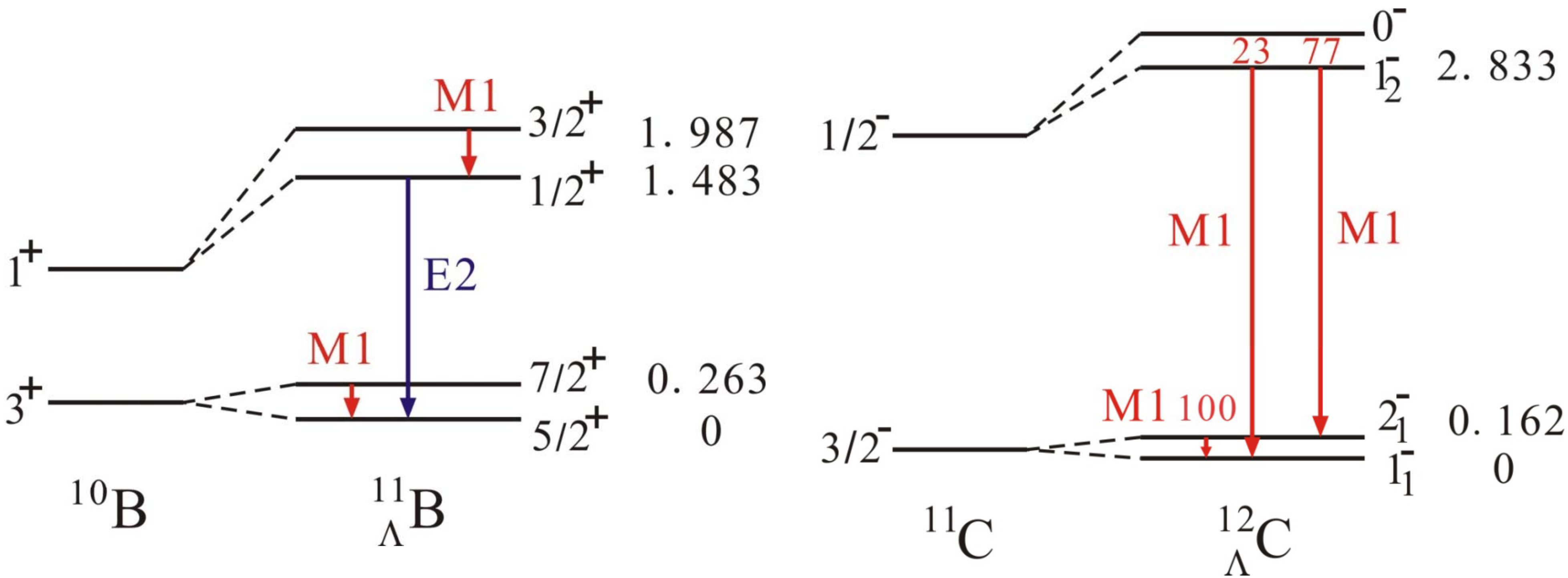






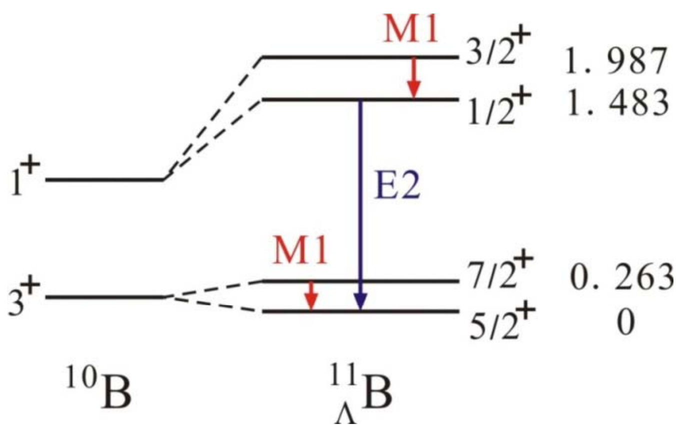
Results & Discussion:

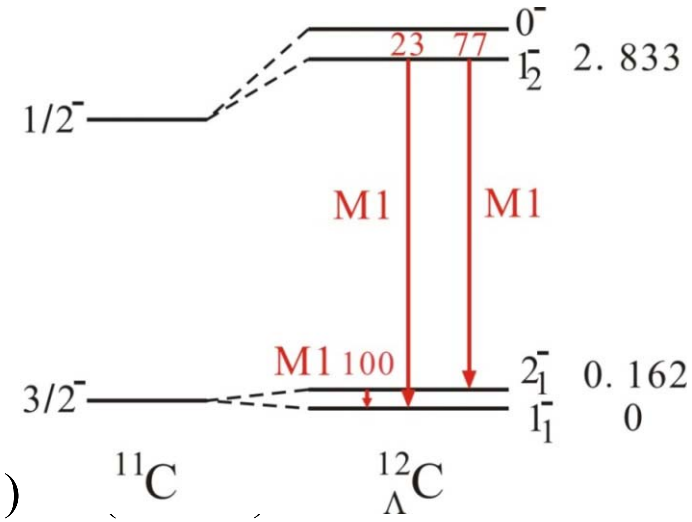
- Hypernuclear level schemes;
- Spin-dependent ΛN interaction;
- ΛNN three-body effects (ΛΣ coupling).



Interaction parameters: S_N

$(\Delta=0.43,\ S_\Lambda=-0.015,\ T=0.03)$





$$E(3/2^+,1/2^+) - E(7/2^+,5/2^+) = E(^{10}B:1^+) + 0.004\Delta - 0.007S_\Lambda - 1.044S_N - 0.025T$$

$$E(1_2^-) - E(1_1^-) = E(^{11}C:1/2^-) - E(^{11}C:3/2^-) + 0.315\Delta + 1.150S_\Lambda - 1.104S_N + 0.635T + \Lambda\Sigma$$

E566: S_N : -0.6~-0.9 MeV;
Previous: S_N : ~-0.4 MeV;
New shell model calculation is necessary.

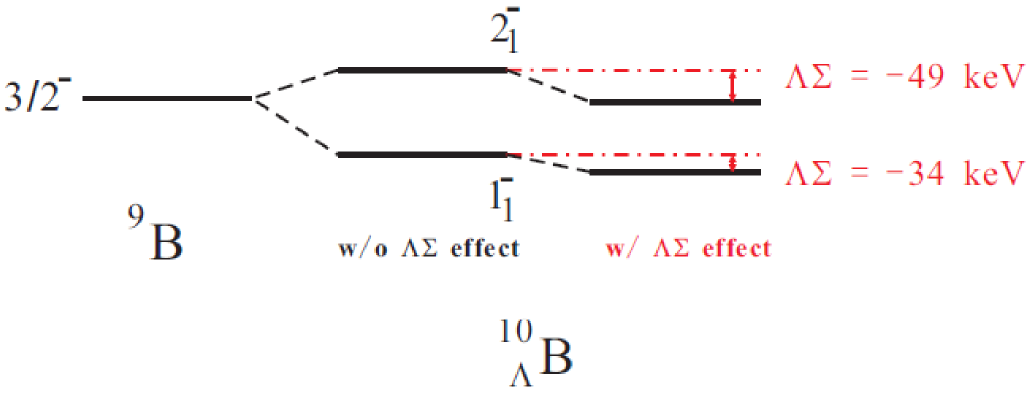
Interaction parameters: Δ

With the S_N value obtained from the present experiment:
${}_{\Lambda}^{11}B$: Δ=0.395 MeV $(S_N=-0.9,\ S_\Lambda=-0.015,\ T=0.03)$;
${}_{\Lambda}^{12}C$: Δ=0.485 MeV $(S_N=-0.6,\ S_\Lambda=-0.015,\ T=0.03)$.

Neglect the discrepancy of the large S_N
and focus on the g.s. doublet spacing:
${}_{\Lambda}^{11}B$: Δ=0.327 MeV $(S_N=-0.35,\ S_\Lambda=-0.015,\ T=0.03)$;
${}_{\Lambda}^{12}C$: Δ=0.337 MeV $(S_N=-0.35,\ S_\Lambda=-0.015,\ T=0.03)$.

Δ value obtained from different hypernuclei:
${}_{\Lambda}^{7}Li$: Δ=0.430 MeV $(S_N=-0.39,\ S_\Lambda=-0.015,\ T=0.03)$;
${}_{\Lambda}^{11}B$: Δ=0.327 MeV $(S_N=-0.35,\ S_\Lambda=-0.015,\ T=0.024)$;
${}_{\Lambda}^{12}C$: Δ=0.337 MeV $(S_N=-0.35,\ S_\Lambda=-0.015,\ T=0.024)$;
${}_{\Lambda}^{16}O$: Δ=0.315 MeV $(S_N=-0.35,\ S_\Lambda=-0.015,\ T=0.023)$.

$\Lambda\Sigma$ effects and ${}_{\Lambda}{}^{10}B$ puzzle



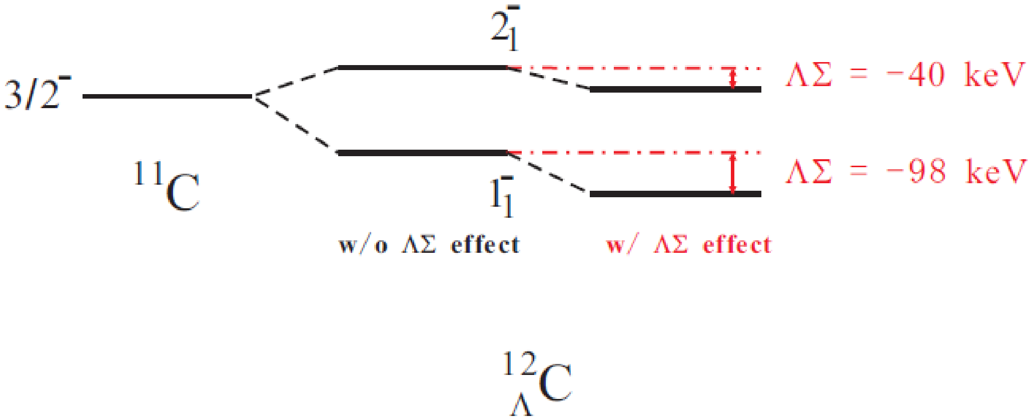
(a) $\Lambda\Sigma$ effect for ${}^{10}_{\Lambda}B$ hypernucleus.

Experimental result: <100 keV

Millener's calculation:

NSC97: E(2)-E(1) = 190 keV+ $\Lambda\Sigma$

✓ESC04: E(2)-E(1) = 125 keV+ $\Lambda\Sigma$
= 34 keV



(b) $\Lambda\Sigma$ effect for ${}^{12}_{\Lambda}C$ hypernucleus.

Experimental result: 160 keV

Millener's calculation:

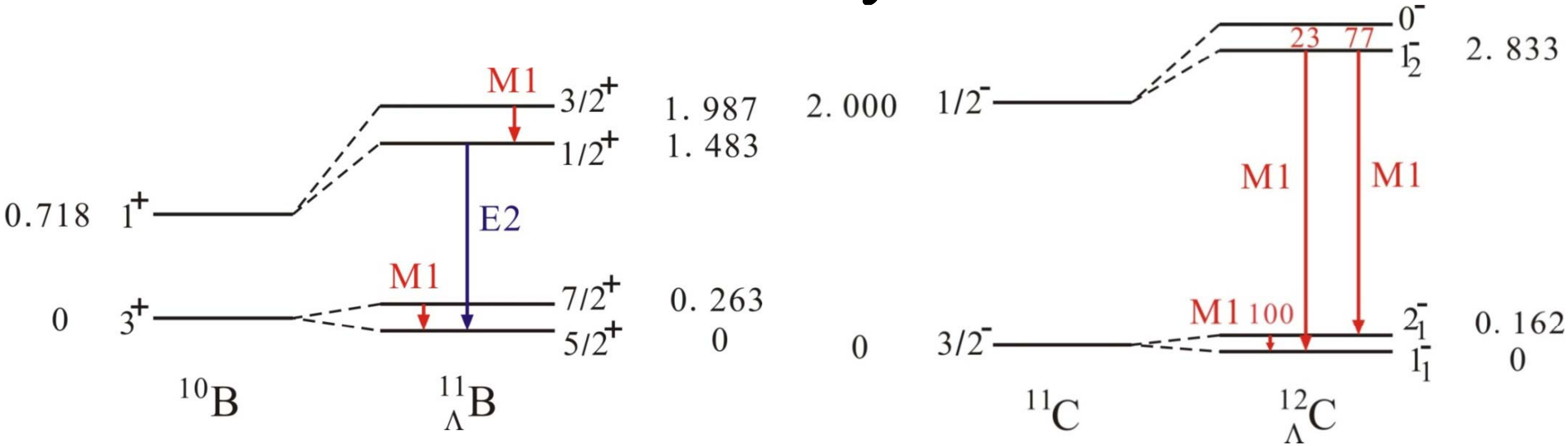
NSC97: E(2)-E(1) = 140 keV+ $\Lambda\Sigma$

✓ESC04: E(2)-E(1) = 63 keV+ $\Lambda\Sigma$
= 167 keV

Summary I

$$
\begin{aligned}
{}^{11}_{\Lambda}\mathrm{B} : M1(\tfrac{7}{2}^{+} \to \tfrac{5}{2}^{+}) \quad E_\gamma &= 262.9 \pm 0.2^{+0.4}_{-0.0}\ \mathrm{keV}, \\
{}^{11}_{\Lambda}\mathrm{B} : E2(\tfrac{1}{2}^{+} \to \tfrac{5}{2}^{+}) \quad E_\gamma &= 1482.9 \pm 0.4 \pm 0.2\ \mathrm{keV}, \\
{}^{11}_{\Lambda}\mathrm{B} : M1(\tfrac{3}{2}^{+} \to \tfrac{1}{2}^{+}) \quad E_\gamma &= 503.9 \pm 0.7 \pm 0.2\ \mathrm{keV}, \\
{}^{12}_{\Lambda}\mathrm{C} : M1(1^-_2 \to 2^-_1) \quad E_\gamma &= 2670.2 \pm 2.6 \pm 0.3\ \mathrm{keV}, \\
{}^{12}_{\Lambda}\mathrm{C} : M1(1^-_2 \to 1^-_1) \quad E_\gamma &= 2833.9 \pm 5.6 \pm 0.3\ \mathrm{keV}, \\
{}^{12}_{\Lambda}\mathrm{C} : M1(2^-_1 \to 1^-_1) \quad E_\gamma &= 161.4 \pm 0.7 \pm 0.3\ \mathrm{keV}.
\end{aligned}
$$

Summary II



➢ S_N: updated shell model calculation is necessary;

➢ ΛΣ coupling: criteria for selecting interaction potential;

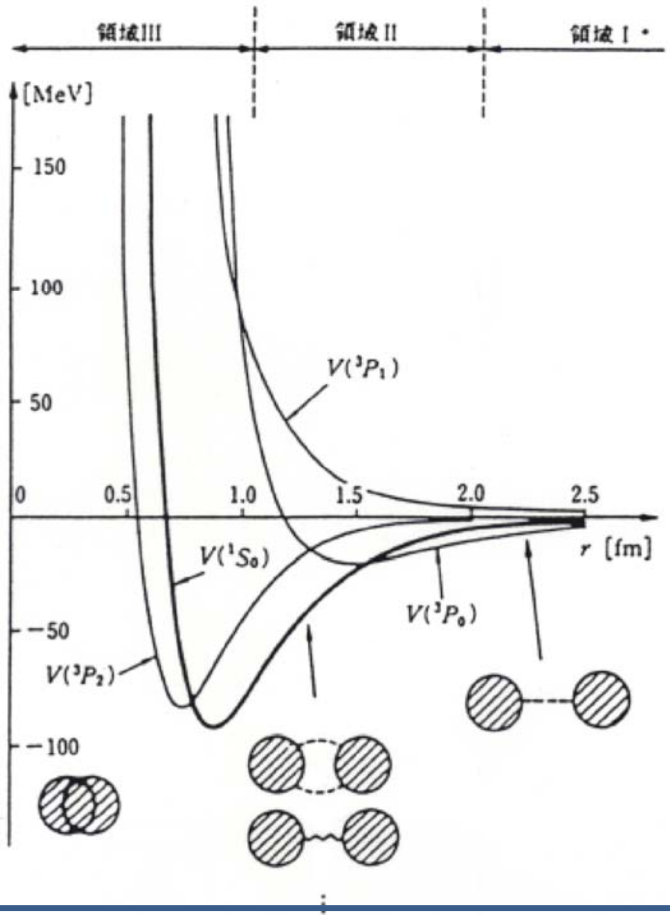
➢ The present data provides important constraints for further theoretical study.

Thank you for your attention.

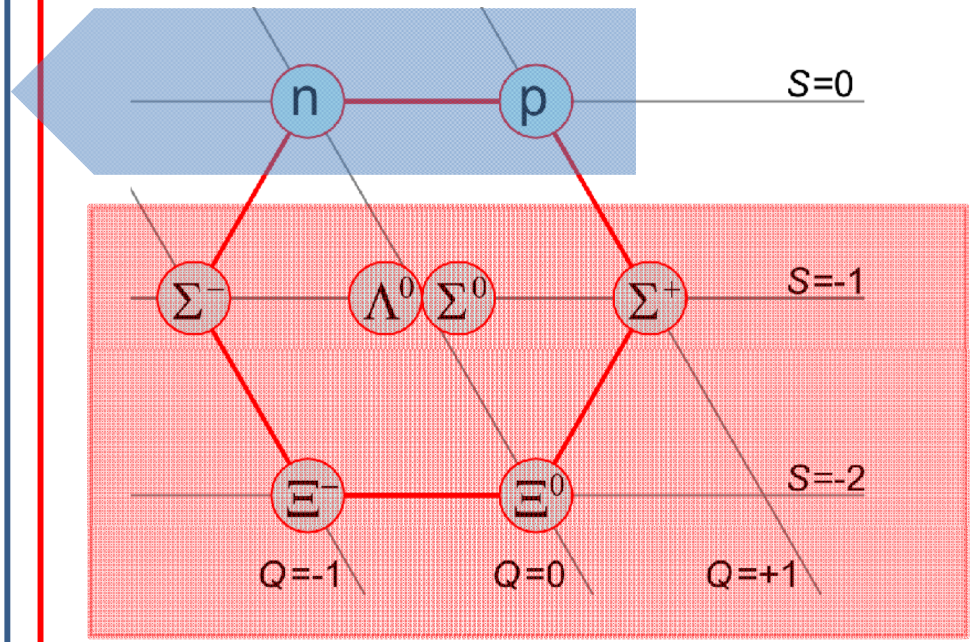
What & Why hypernuclear physics

Nuclear physics:

✓nucleon-nucleon (NN) interaction:
✓sophisticated models;
✓collective effects (many-body problem)



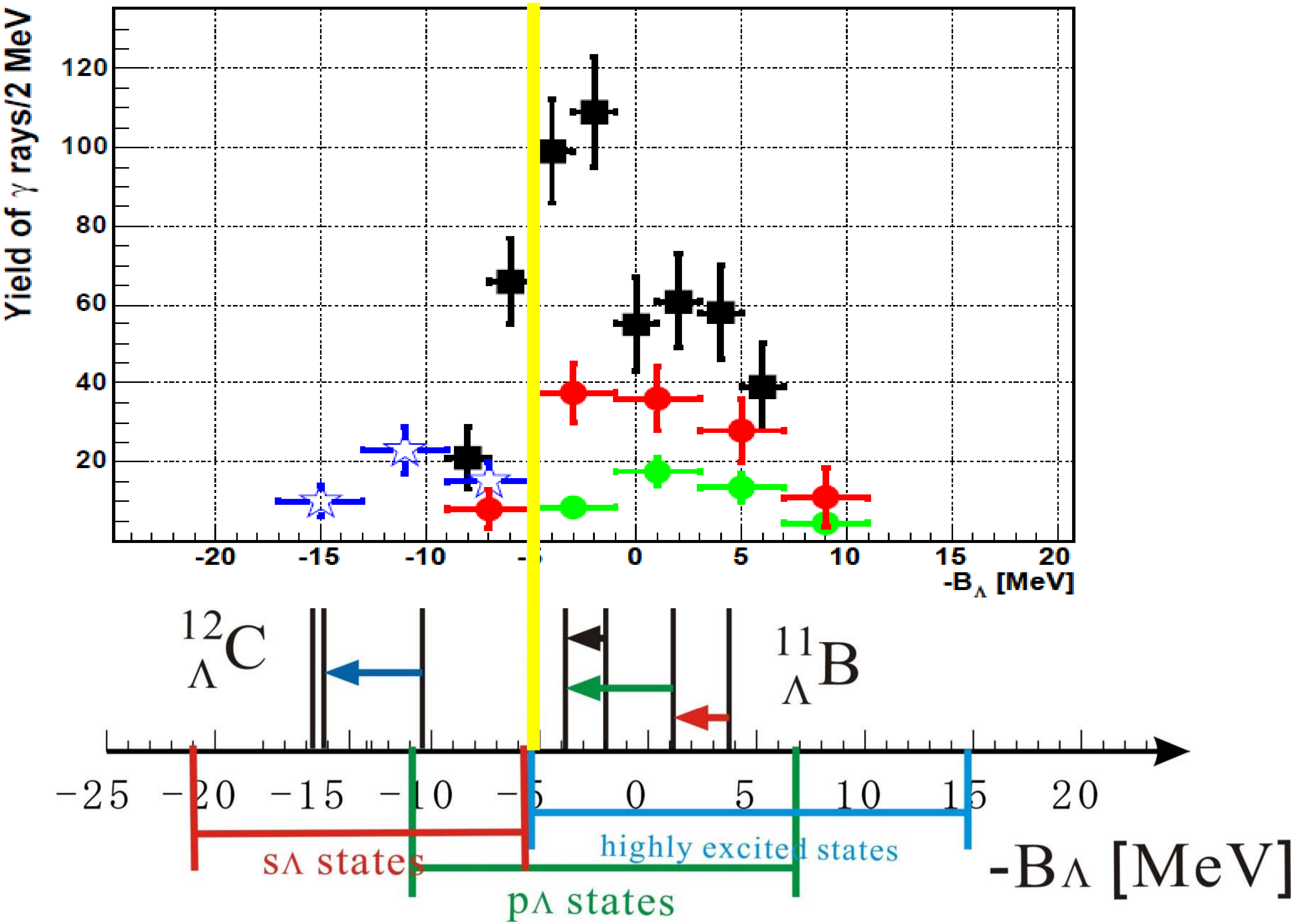
Unified baryon-baryon interaction



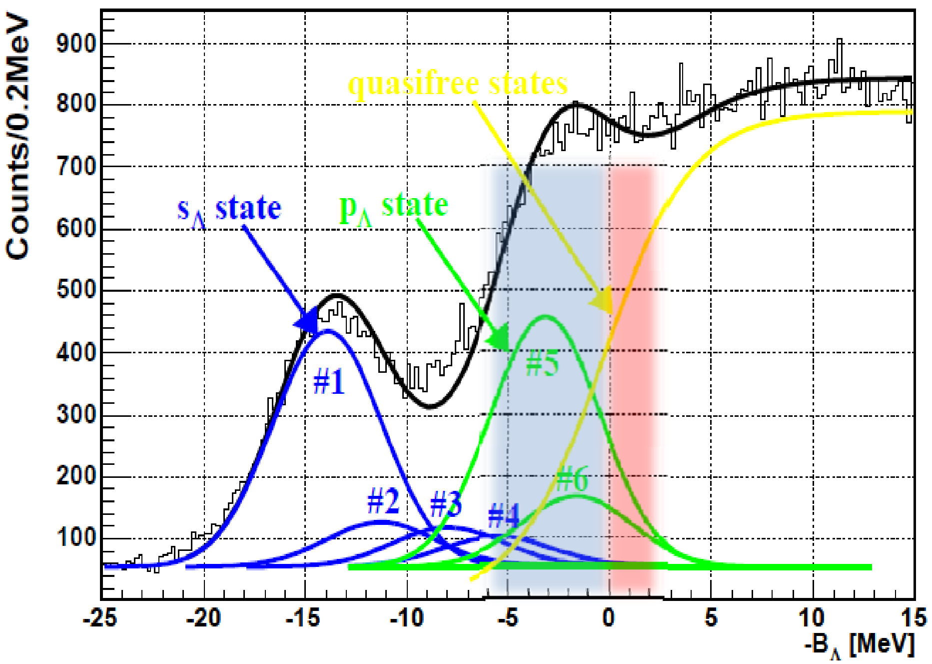
Hyperon & hypernuclear physics

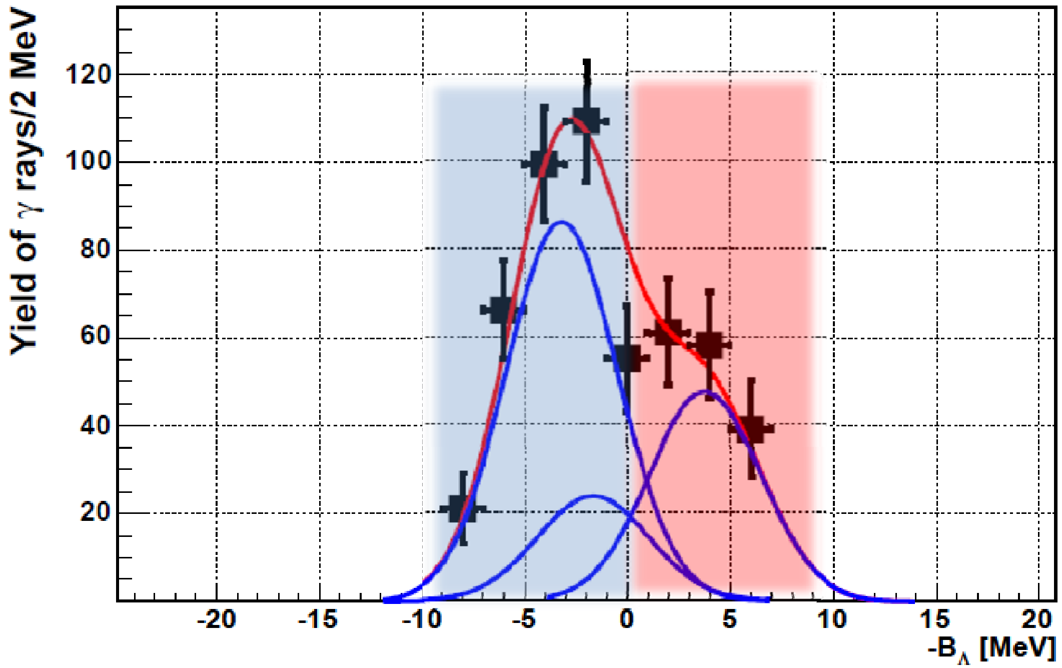
✓YN interaction;
✓extension of nuclear physics;
✓expands our view of matter.

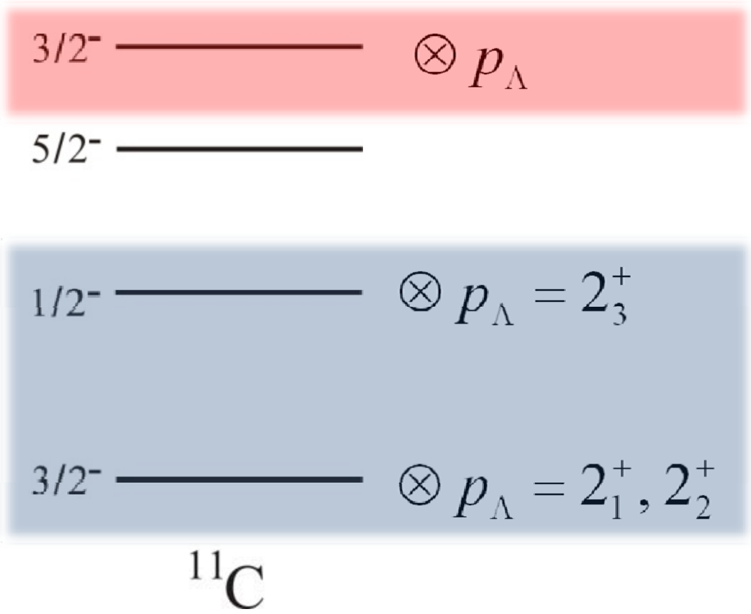
γ-ray yield vs. $-B_\Lambda$: qualitatively consistent

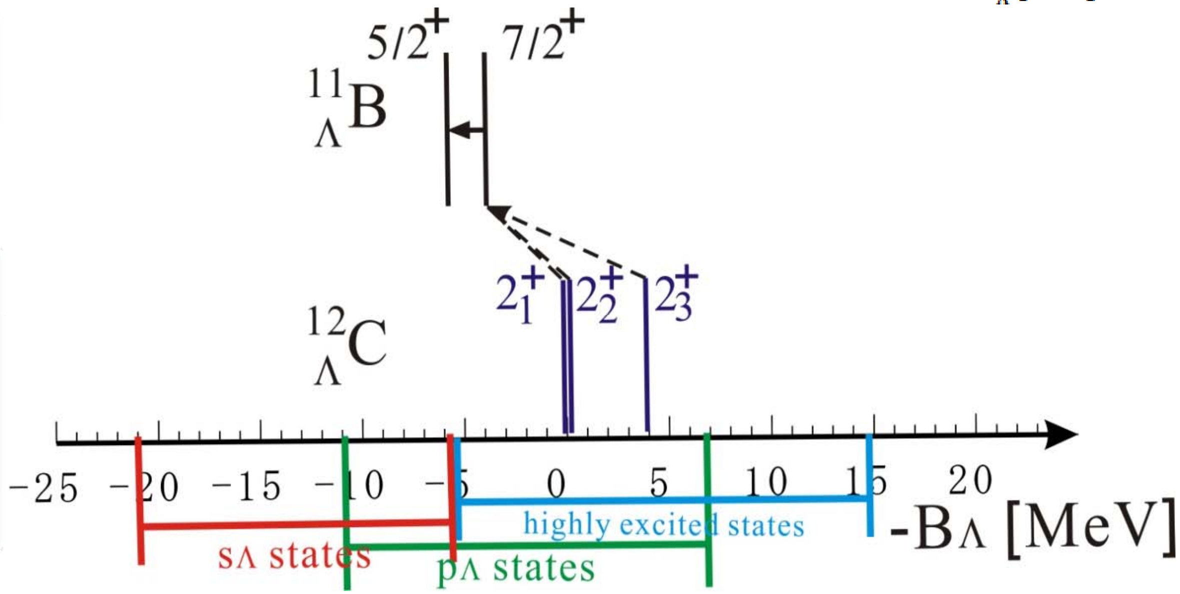


γ-ray yield vs. $-B_\Lambda$: new core excited state

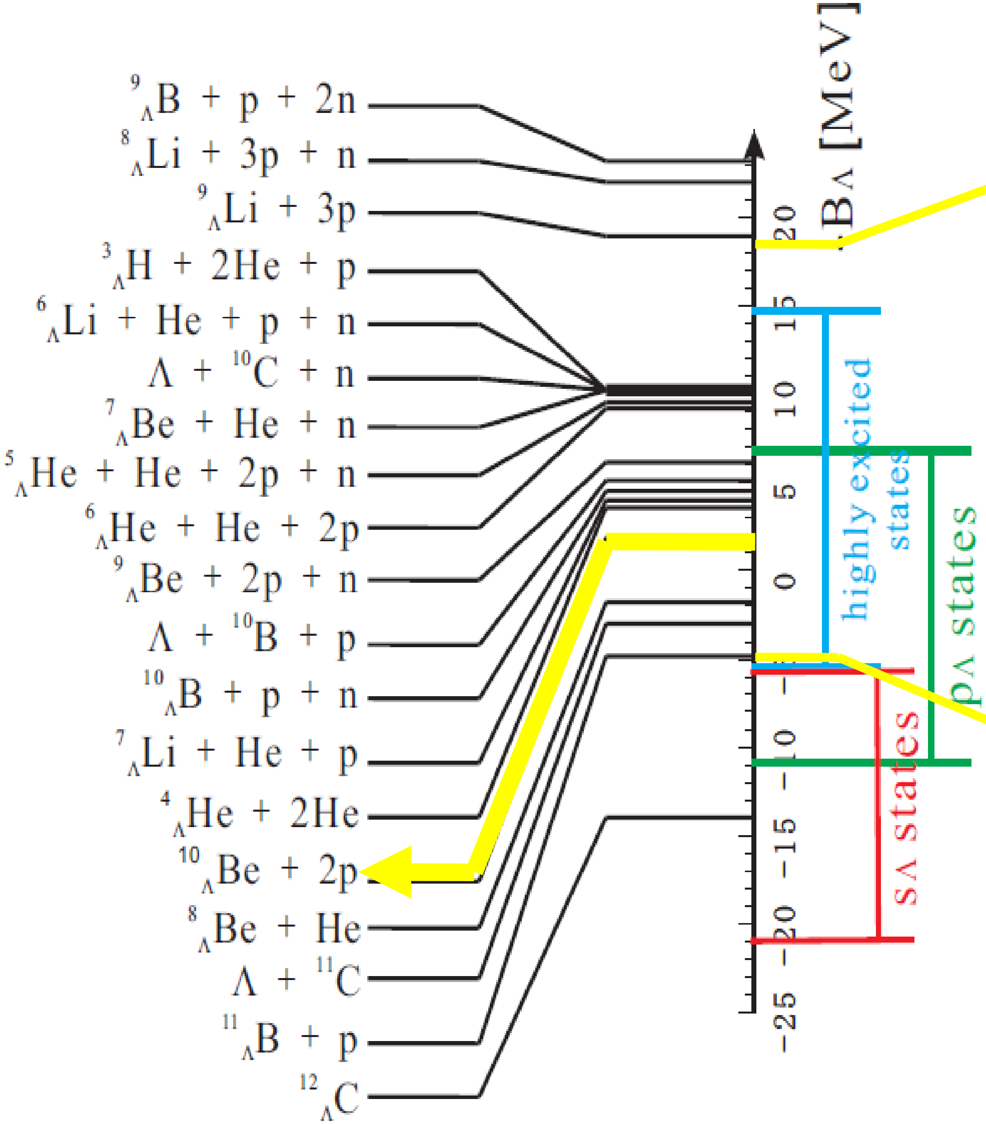


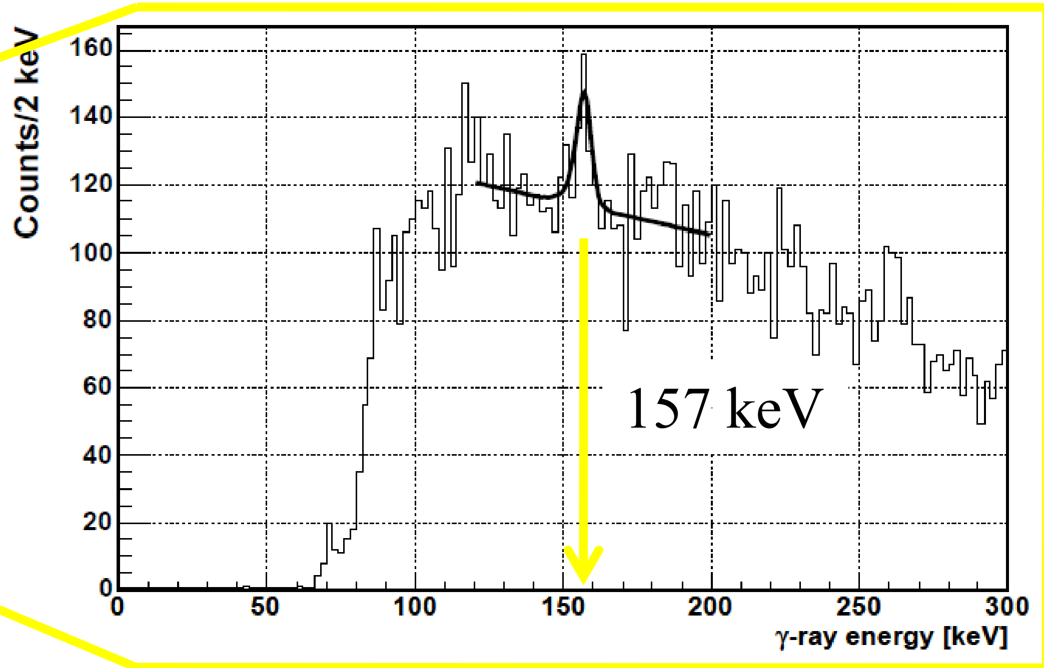






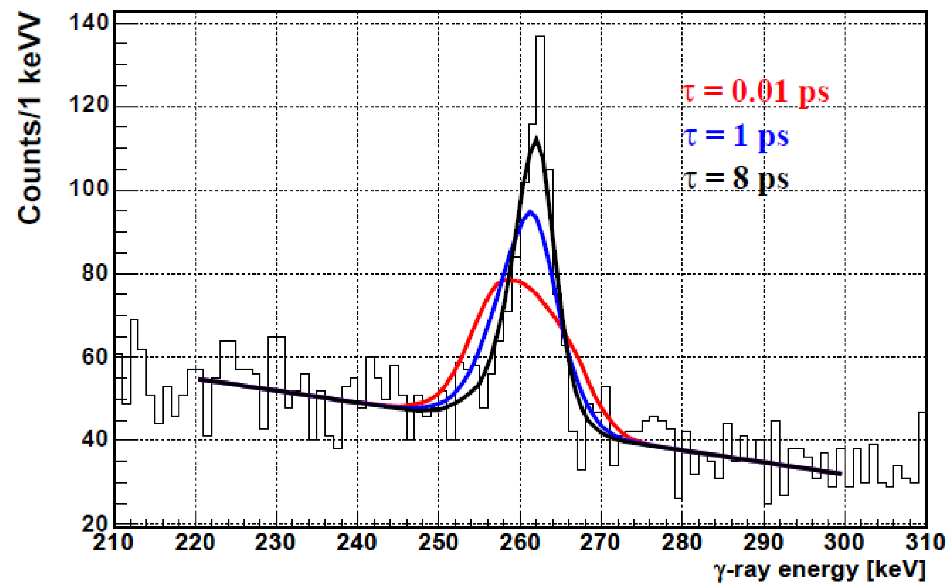
γ-ray spectrum from hyperfragments
(energetically possible decay products of $_{\Lambda}^{12}C$)

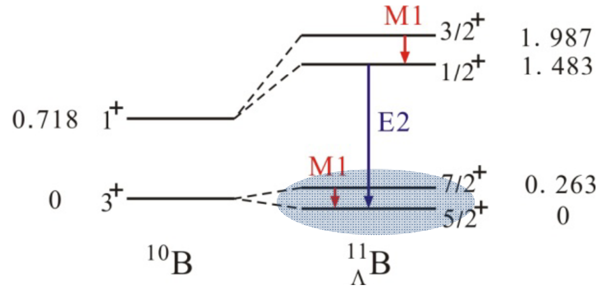




Small energy;
long lifetime;
M1 transition from $_{\Lambda}^{10}Be$?

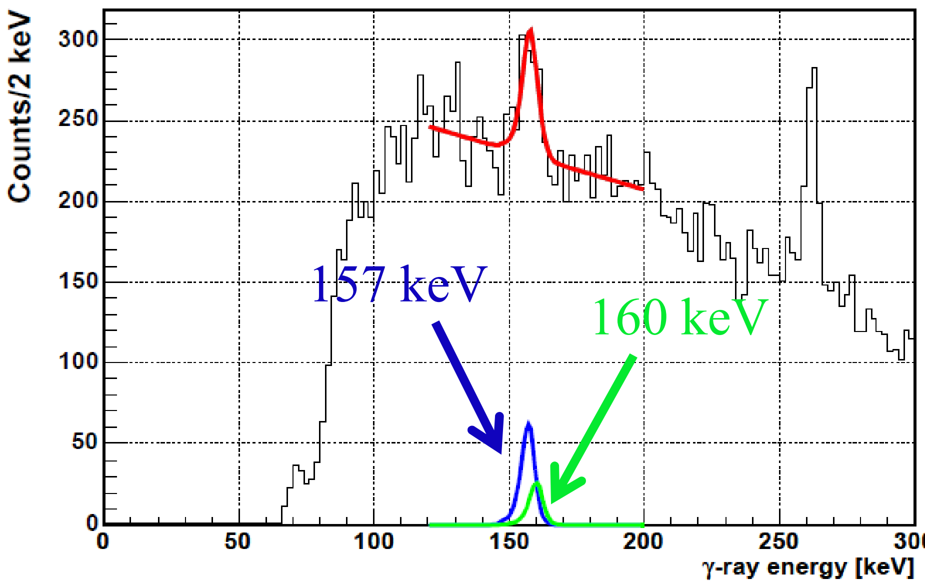
g_Λ factor inside nuclear medium: two methods

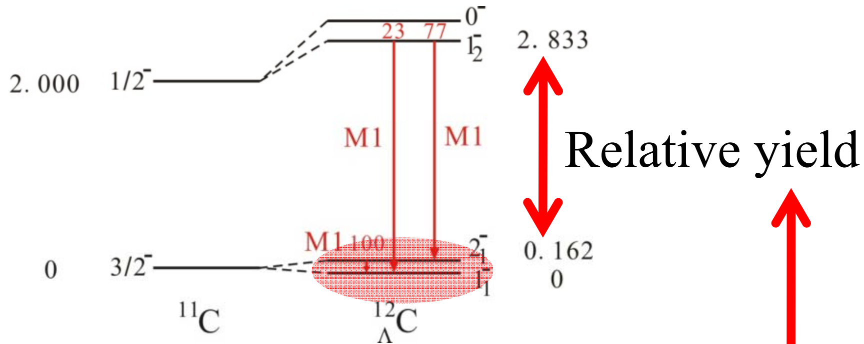




$$\tau > 7\,[\text{ps}] \Rightarrow g_\Lambda > -1.49\,[\mu_N]$$

$$(g_\Lambda = -1.226 \pm 0.008\,[\mu_N]\text{ in free space})$$





Using weak decay lifetime as reference:

$\Gamma_{weak} = 230.7 \pm 16.3\,[\text{ps}]$;

Assuming g_Λ in free space $\Rightarrow 34\%$;

Experimental data $\Rightarrow 19 \pm 12\%$.